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PRELIMINARY DIAGNOSTIC PROCEDURES FOR RADON CONTROL

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ABSTRACT

A preliminary set of analytical procedures for use in diagnosing radon entry mechanisms into buildings is described. These diagnostic methods are generally based on the premise that pressure-driven flow of radon bearing soil gas into buildings is the most significant source of radon in homes with elevated concentrations, although procedures to determine the contributions of other potential sources such as building materials and potable water to indoor airborne concentrations are also included. A series of graphical flowcharts are presented that develop a logical sequence of events in the diagnostic process, including problem diagnosis, selection and implementation of mitigation systems and post-mitigation evaluation. The initial problem assessment procedures rely on an organized set of measurements to characterize the structure, the surrounding soil and the likely entry pathways from the soil into the building interior. The measurement procedures, described in detail in the text, include radon grab sampling under both naturally- and mechanically-depressurized conditions, visual and instrumental analysis of air movement at various substructure locations, building leakage area tests, and soil characterization methods. Post-mitigation evaluation procedures are also described. Samples of various data forms and test logs are provided.

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I. INTRODUCTION

With the discovery of high indoor radon (Rn-222) concentrations in a significant number of residences since the late 1970's, it has become important to develop a better understanding of the mechanisms of radon movement into and accumulation in buildings and suitable methods for controlling or eliminating the accumulations. In general, earlier research has found that the most significant source of indoor radon is the soil surrounding the building shell from which radon migrates into the building transported by pressure-driven flow of soil gas. A few of the factors influencing the radon entry rate include indoor-outdoor air temperature differences, wind loading, soil characteristics, construction details of the building superstructure and substructure, and coupling between the soil and the substructure.

In order to further investigate radon entry and radon control techniques, the U.S. Environmental Protection Agency (EPA), the Department of Energy (DOE), and the New Jersey Department of Environmental Protection (NJDEP) are funding an intensive study in fourteen northern New Jersey homes. The research is being conducted by the Lawrence Berkeley Laboratory (LBL) in seven homes and collaboratively by Oak Ridge National Laboratory and Princeton University in a second set of seven homes. Since few studies have attempted to relate influencing factors to entry rates and to investigate the importance of these factors on systems designed for radon abatement, the following overall objectives were established for this project.

- Extend our understanding of the fundamentals of soil gas flow and radon entry into buildings and improve our basic knowledge of factors that influence the entry rate.

- Develop a better understanding of the success or failure of certain mitigation techniques and of the operational ranges of key parameters that affect the utility of these techniques.

- Refine and develop analysis procedures for diagnosing radon entry mechanisms and the selection of appropriate control systems.

The basic research plan for this project has four main operational components: 1) house and site characterization measurements, 2) baseline and continuous monitoring of environmental and building parameters, 3) diagnostic procedure development, and 4) installation and operation of selected mitigation techniques.

This report focuses primarily on item 3, development of diagnostic procedures. Diagnostic procedures are defined here as an organized and logical set of measurements, tests, and observations that are necessary for identifying the specific means by which radon enters and accumulates in a particular structure. In addition, these procedures should point the way to a suitable system or technique for controlling the indoor radon levels. These procedures may also encompass follow-up measurements, tests, and observations important in optimizing mitigation system performance. This development effort builds on the previous, on-going, and generally unpublished work of others, including Scott, Tappan, Henschel, Ericson, and Brennan, as well as on the basic scientific understanding developed by Nazaroff, Nero, and others at LBL. Hopefully, it provides a format for refinement, reduction and interpretation of the measurements and observations necessary for selecting an appropriately designed, effective, and economical system for controlling indoor radon levels in a majority of existing U.S. single-family houses with elevated radon concentrations.

A. Study Methodology

The 14 participating New Jersey homes were selected from a larger group of approximately 130 New Jersey homes based on various criteria including representative construction types, soil characteristics, and accessibility to interior basement walls and floors. With the homeowners' consent, a large number of diagnostic measurements have been made, suitable control systems have been selected, installed (in some houses a second competing system will be installed) and operated, and follow-up diagnostic measurements are being performed while system performance is monitored and optimized. This process is still in progress. Because revisions will be and are being made to the procedures discussed here, this report should be considered preliminary.

The other major research objective, that is developing a better understanding of the fundamental factors influencing radon entry, goes beyond but is supportive of the development of diagnostic procedures. Tasks in support of this broader objective include continuous data collection, periodic measurements and specific experiments conducted throughout the project. Measured parameters are detailed in Table 1. In the seven-home LBL study, radon is being continuously monitored in one substructure location and one first floor location using continuously pumped room air sample through an alpha scintillation cell and counter and recorded on a data logger. These devices are operated during premitigation baseline conditions to establish pre-existing indoor radon concentrations and during post-mitigation measurement periods. Other parameters are also recorded on the data logger such as continuous radon concentrations below basement slabs, indoor and outdoor temperatures, subslab soil temperatures, near-structure soil temperature and moisture, windspeed and direction, and pressure differentials continuously monitored across the basement slab and across the substructure/ambient interface. Seven-day average indoor water vapor concentrations are monitored with passive samplers. Barometric pressure and rainfall are continuously monitored at one house. In addition, occupants are requested to complete forms summarizing daily activities that might affect the indoor environment. Technicians also periodically conduct other measurements. Evaluation of daily and seasonal impacts on radon entry and mitigation system performance will then be possible. There will be little additional discussion of these efforts in this report.

B. Limits of Discussion

This document is not intended to provide detailed guidance for the practical application of diagnostic procedures. Many of the techniques and measurements used in these diagnostic procedures are solely for the support of specific research aspects of this project. As a result, few private consultants or contractors will be capable of purchasing the equipment or receive the training necessary to perform the measurements utilized here while still being competitive and profitable in the marketplace. In fact, the use of the diagnostic procedures discussed here may be prohibitively expensive to building owners and managers and, therefore, will see little use in their present form. This may be particularly true for houses with concentrations between 4 pCi/L* and approximately 20 pCi/L, since the perceived health risk at those levels may not be significant enough to warrant large expenditures for diagnosis and mitigation.

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*This report discusses radon concentrations in units of picocuries per liter, pCi/L, still commonly used in the U.S. The conversion to SI units is 1 pCi/L = 37 Bq/m^3.

TABLE 1: Project Measurement Activities

1) Parameters to be monitored continuously:

- indoor radon concentrations (various locations within the house), and possibly radon progeny concentrations (smaller subset of houses),
- outdoor and indoor temperatures,
- meteorological parameters at each site, including windspeed and direction,
- pressure differentials across the building shell (various locations),
- soil moisture and temperature, and
- barometric pressure and precipitation at one central site.

2) Parameters to be monitored periodically:

- soil air permeability,
- ventilation rate,
- indoor water vapor,
- soil gas radon concentrations at selected locations, and
- occupant effects and activities, including operation of a fireplace or wood stove, forced air furnace systems, exhaust fans, *etc.*

3) Parameters to be measured once or occasionally:

- effective leakage area,
- radon progeny concentrations,
- soil characteristics (at LBL), including permeability, grain size distribution, soil radium concentration, and emanation ratio,
- frost depth and snow cover,
- pressure-field mapping to determine coupling between building shell and surrounding soil,
- tracer gas (SF_6) injection in soil and resulting concentrations within the building shell (if utilized), and
- additional parameters specific to the mitigation technique under investigation, such as the flow rate of air through a block wall or subslab ventilation system, or tracer gas analysis of flow pathways.

However, this current set of methods for diagnosing radon problems is necessary for the development of practical and useful procedures that can be used by persons requiring less technical training and equipment. Over the next several years, further refinements (including the assembly of "expert systems") may make diagnoses easier and improve the probability for successful selection of appropriate radon control systems.

An area that requires additional work is that of mitigation system selection. At present, data collected during diagnostic measurements are valuable only to those already familiar with selection and installation of mitigation systems. Defining the process that rigorously indicates selection of the "correct" control system for a particular house is not an objective of this work, although some progress is made toward that goal.

Finally, this is not a report on the details of specific mitigation techniques. Other papers (some of which are listed in the references) discuss these techniques and systems more fully. Details and evaluations of the mitigation systems used in this study will be subjects of a later report.

II. OUTLINE OF GENERAL DIAGNOSTIC PROCEDURES

The premise for much of the diagnostic procedures developed and discussed here is that the pressure-driven flow of radon-bearing soil gas is the most significant source of radon in houses with elevated concentrations. While further discussion of this premise is beyond the scope of this report, the reader should refer to DSMA, (1985) and Nazaroff, *et al.*, (1985a, 1985b, 1986) for additional discussion. On the other hand, other potential sources of radon, such as water and building materials, are also included in the diagnostic procedures discussed here. A good overall review is found in Nero and Nazaroff, (1984).

The procedures described here rely on a series of individual site-specific observations and measurements of air flow, pressure differentials, radon concentrations and near-building material characteristics. This collection of measurements is then used to identify primary radon sources (water, building materials, soil) and most probable radon entry points and mechanisms. Various tools and instruments (see Table 2) are necessary to conduct the diagnostic procedures discussed here and this report assumes that the reader has prior experience with flow and pressure measuring devices, and alpha particle counting techniques. Samples of forms for recording this diagnostic information are found in Appendices A, B, C, D and are referred to in the text.

Some investigators have used gamma radiation surveys as a method of locating radon source materials. Making and interpreting results of such surveys in buildings appears to pose a number of difficulties and we have not utilized this technique here. Since soil gas flows are the most significant source of radon in houses, the location and extent of penetrations through the building shell, along with physical characteristics of the surrounding soil (such as air permeability) are the most important determinants of radon entry and source locatoin. Variations of apparent radium and/or radon concentration in the soil near the building may not be correlated with entry locations. The methods we discuss here, particularly air sampling for radon at suspected entry points and in areas where radon accumulation is likely, provides a more direct method of identifying radon sources and entry locations.

Radon, not radon progeny, is measured before, during, and after diagnostics and is the contaminant on which control efforts are focussed. In its role as progenitor, control of radon also controls radon decay products, which are responsible for the adverse health risks associated with radon exposures. There are some potential mitigation measures directed at progeny control only, such as air cleaning. These are not considered here.

Before diagnostic procedures for radon control are employed, the indoor radon concentrations on any occupied floor in a particular structure should be verified during the heating seasons as being greater than the recognized guideline. Methods and procedures for determining indoor radon concentrations during non-heating season periods are being studied. However, relationships between heating season and non-heating season concentrations in homes with elevated concentrations have not been established. In this report, EPA's suggested guideline of 4 pCi/L annual-average concentration is used as a conservative heating season worst case target in diagnosis and in determination of successful mitigation. Ultimately, these heating season measurements would predict the annual average concentration. However, at this time, we are unable to make that prediction. The basic procedure here can be used with different guidelines. For example, in an area with many homes with indoor concentrations greater than 20 pCi/L, these houses might be the main objective of diagnostic and remedial efforts during the next several years.

TABLE 2: Instruments and Equipment

Radon Grab Sampling:	Alpha scintillation cells Portable photomultiplier tube counting station Hand pump with sample tube and 0.8 μm filter Compressed air or nitrogen for cell flushing Vacuum pump for evacuating cells (70 cm, 27 in. Hg vacuum)
Air Leakage and Flow Measurements:	Calibrated-flow blower door (6800 m^3h^{-1}, 4000 cfm @ 5 Pa) Pitot tubes (electronic or liquid-filled manometers: 1-50 kPa) Hot wire anemometer (with temperature sensing element) Smoke tubes Industrial vacuum cleaner (170 m^3h^{-1}, 100 cfm @ 2m, 80 in. H_2O pressure) 1.5 m (5 ft.) flow sections of : 7.6 cm (3 in.) PVC with coupler 15 cm (6 in.) galvanized duct Non-toxic tracer gas (SF_6, Freon 12) Tracer gas detection instrument
Soils Characterization:	Soil core and auger samplers 3/4" reversible electric drill Soil air permeability device Sliding hammers Various diameter drill bits, including some attached 1.5 m (5 ft.) long extensions 1.5m (5 ft.) long probe pipes
Inspection Equipment:	Stiff wires Telescoping mirrors Portable gamma spectrometer Fiber optics scope
Tools:	3/8" variable speed hand drill Masonry bits 1/2" hammer drill Impact bits Pocket flashlights Hand sledge Pry bar Pipe wrench Locking pliers Adjustable wrenches Portable lights Step ladders Long blade screwdriver
Miscellaneous:	Forms Inspection hole plugs Epoxy-based mortar patch or hydraulic cement Duct tape Duct seal 0.3, 0.6, 1 cm (1/8, 1/4, 3/8 in.) diameter tubing Various-sized hypodermic needles Plastic film Thermometers: electronic and mercury-filled glass Silicone sealant

Due to the potential for large variations in indoor radon concentrations in the same house, short term measurements (less than 4 days) are not adequate to eliminate the possibility of false positives or negatives. Therefore, two separate 7-day measurements using a continuous radon monitor or one 14-day minimum alpha track average measurement of indoor radon levels during the heating season are recommended here. If concentrations during both 7-day periods are higher (or lower) than the guideline, one can be more confident that the measurements represent typical heating season indoor concentrations for that house. If the concentrations from these measurements do not replicate, *i.e.*, one measurement is above the guideline while the other is below, then a third (and perhaps of longer duration) test should be conducted or diagnostic procedures begun. The EPA recommends a slightly different schedule of follow-up measurements based on the initial test result concentrations (Ronca-Battista, *et al.*, 1986).

III. DISCUSSION OF DETAILED DIAGNOSTIC PROCEDURES

A "General Plan for Radon Control", shown in Figure 1, outlines the basic process for mitigating elevated radon levels. Once a structure is determined to have a radon problem, a survey of the structure is conducted that characterizes soil-linked radon entry points in the building shell and evaluates potential non-soil sources. After reviewing the results of the diagnostic measurements, suitable options for radon mitigation are considered and a final plan for the control system(s) is developed. Follow-up measurements of indoor air concentrations and system operating conditions are made once the installations are completed. If follow-up short-term diagnostic measurements of indoor radon concentrations are still greater than the guideline, then modifications or additional system options must be installed. For apparently successful installations, the system is tuned for improved efficiency (*i.e.*, effective performance with reduction in system size requirements) and more economical operation and the reduced indoor levels are verified with a 14-day average heating season measurement.

The following discusses details of the various diagnostic methods, techniques, and procedures currently under development. Figures 2-7 in flowchart-graphical form show a logical sequence of steps that will assist in guiding the reader through the measurement and evaluation process. We emphasize again that this system of diagnosis is for research purposes and is intended to serve as the basis of somewhat simpler approaches for general application.

A. Premitigation Diagnostics

A complete evaluation of a house with elevated radon concentrations should consider all sources, including soil-based sources such as convective soil gas flow through cracks and holes and diffusive flow through the building membrane, as well as non-soil sources such as water and building materials. Problem diagnosis begins with Figure 2 #1, "Conduct Visual Inspection". This building survey is undertaken using a checklist (Appendix A) and a form such as in Appendix B to identify all potential areas that may be contributing to elevated indoor radon levels. Although the majority of indoor radon problems can be traced to soil-based convective or diffusive flows, the survey encourages an initial inspection of building materials and a measurement of water radon concentrations where water is from a local well. See Figures 3 and 4.

1. Characterize Structure and Identify Soil Gas Entry Points

Identify Entry Locations

Convective flow of soil gas containing radon into buildings is the most frequent cause of excessive radon concentrations in indoor air and contributes to elevated indoor radon levels when there are 1) entry locations through the substructure where radon bearing soil gas can pass into the building, 2) relatively higher soil gas radon concentrations in the soil near the structure, and 3) sufficient soil air permeability to permit flow of soil gas.

During the visual inspection of the house, soil-based radon entry possibilities are tentatively identified. The survey questionnaire and floor plans (Appendices B and C) are especially useful tools in identifying likely entry locations. Examples of drawings/floor plans are illustrated Appendices C1-C5. The survey questionnaire form requires very detailed and specific information about construction type, materials, conditions of materials and surfaces, mechanical equipment, imperfections that can allow soil gas entry, and building occupancy. This information is essential to a

thorough understanding of the building and its operation and ultimately to the design of a suitable radon control system(s).

The visual inspection should include probing of likely entry points in the substructure. Using a stiff wire, screwdriver, and chemical smoke tube, and possibly a fiber optics viewing scope, all substructure surfaces in contact with the soil should be examined to determine if cracks and holes may penetrate or connect to the soil. Under natural heating season conditions the smoke tube may detect soil gas movement in or out of the opening. Significant openings would include wall or floor cracks and holes, the interface between various masonry material surfaces such as floor/wall joint (where the floor slab is poured against the substructure wall), gaps around utility services penetrations, floor drains, and the tops of block walls. These should be noted on the survey form and located on the floor plan.

To allow for additional inspection sites, tests of subsurface pressure field extent and ventilation communication tests, and subsurface grab sampling, small 1 cm (3/8 in.) diameter holes are drilled into and through various substructure surfaces (0.6 cm, 1/4 in., diameter holes for hollow block walls). The number and location of these holes depend on the configuration and size of the substructure. Our current experimental practice requires approximately three to four slab holes: one in each corner of the slab (approximately 1 m; 3 ft. from each wall), one hole through each wall (approximately 1/3 the height of the wall above the floor), and one hole drilled into an open cell of every sixth block in the second row of blocks above the slab floor. In addition, a larger central hole, 2 to 4 cm (3/4 to 1-1/2 in.) in diameter is drilled through each slab and at least one block wall so that a powerful industrial or shop-type vacuum cleaner can be attached to conduct subsurface communication tests. Holes are plugged with a removable temporary seal of putty-like material (duct seal, Mortite®) until the completion of all diagnostics and mitigation. Upon completion of the mitigation, the holes will be permanently sealed.

Alpha-scintillation-cell Grab Samples of Radon

To determine if any building zones have relatively high indoor radon levels that would help identify a predominant area of radon entry and to attempt to more specifically locate substructure entry points, grab samples of air are then collected. They are taken from each unique building zone (garage, first floor, second floor, basement, crawlspace, rooms that are slab-on-grade), the ambient outside air, and selected entry points and inspection holes. These samples are taken under natural conditions (Figure 2 #2) in the structure, influenced only by the existing environmental variables, such as wind speed, outside air temperatures soil moisture and temperature. Measured values of these variables should be recorded at time of sampling (see Appendix D1). Grab samples are collected again with the building mechanically depressurized, as discussed below.

Alpha scintillation cells (Lucas cells) with zinc sulfide coating and 100 - 200 ml internal volume are used to collect the samples. Prior to use, these cells are purged of any radon or radon progeny using filtered outside air or aged compressed gas (air or nitrogen), and a 2-minute background count is performed with a portable photomultiplier tube scintillation counter to ensure that the cells are free of radon. A gas sample is taken with a sample probe consisting of small diameter tubing, a hypodermic needle, or other appropriate fitting, an 0.8 μm filter assembly, the Lucas cell and a small hand-operated vacuum pump. The hand pump is used to flush the sample train with the gas sample. The cell, previously evacuated with the hand pump, is then opened and allowed to pull in the intended sample. Sufficient time is allowed for the cell to reach atmospheric pressure before the cell is sealed.

Since these samples are to be used only for diagnostic purposes and an indication of the relative concentration of radon gas, it is not necessary to wait for the radon gas and progeny in the cell to reach equilibrium (approximately 3 hours). It is important to realize that air samples collected from test holes or entry points may initially contain ^{220}Rn, thoron, as well as ^{222}Rn, radon. Potential effects on the total alpha activity observed in the cell due to ^{220}Rn and ^{220}Rn progeny decay can be minimized by waiting at least 10 min before cell counting. The cells are analyzed by counting the alpha activity in a photomultiplier tube counting station. Semi-quantitative results sufficient for comparison of radon concentrations between samples can be obtained by counting the activity for 2 minutes. For this short counting interval, care must be taken to avoid exposing the coating on the cell walls to bright ambient light levels. The light may activate the coating, producing scintillations that might be registered by the counting station. These spurious scintillations are very short-lived and can also be minimized by allowing approximately a one minute delay between the time the cell is placed in the counter and the time counting commences. Following counting, the cell should be purged immediately as indicated previously and not used again for sampling for another 24 hours. Cells used for measurement of high concentrations can be segregated for use only with high concentrations. These cells should be checked for background before use. In addition, background activity should be checked in all cells after at least every ten samples to monitor cell contamination.

Other grab samples should be taken after the building (or substructure only) has been depressurized for approximately 30 minutes using a variable speed fan capable of developing a -10 Pa pressure difference between the substructure and the outdoor atmosphere (Figure 2, #3a-h). This simulates maximum heating season pressure-driven forces on soil gas entry. While a smaller pressure difference (-3 to -5 Pa) is probably more typical of heating season conditions, the slightly larger difference encourages a more rapid radon entry response, tends to swamp variable environmental effects (wind speed) during the procedure and minimizes radon depletion in the nearby soil that might occur at higher pressure differences.

The mechanical depressurization may not cause representative distribution of radon throughout the structure, depending on the distribution of the building's air infiltration leakage area and location of the depressurization fan. Therefore zone room air grab samples from the building may not suitably represent natural condition radon concentrations.

Grab samples should be taken from all suspected entry points, drilled test holes, inside firred wall stud cavities, floating slab gaps (French drains), and from wall and floor cracks and wall/floor joints. The last two samples are often difficult to obtain. One method that minimizes dilution of radon by room air involves taping over the crack or joint approximately 0.6 m (2 ft) to either side of the sample location. Then, depending on the width of the gap, a small tube, or if necessary, a hypodermic needle is inserted into the gap through the tape and a sample is withdrawn. For French drains, both ends of the taped section should also be plugged to prohibit ventilation of the sample space. After collection, all samples are then counted and analyzed.

Based on previous experience, samples from locations with concentrations less than or equal to the room air concentration are unlikely to identify radon entry source points. Those with concentrations approximately two or three times room air concentrations are possibly significant entry locations, and those with concentrations greater than three times room air levels indicate likely source points for significant radon entry.

Soil Gas Movement

As an estimate of the mobility of soil gas under slabs, within block walls and through suspected entry points, air movement can be qualitatively measured. The amount of soil gas that can pass through a crack or hole may be valuable in defining its importance as a radon entry point. However, some minute cracks will show no visible evidence of air movement, yet may still contribute to the flow of radon-bearing soil gas into the building interior.

To check for the flow of soil gas at the suspected entry points and drilled test holes, substructure depressurization is increased to -30 Pa, which exaggerates any natural air movement (Figure 2, #4). Using chemical smoke from commercially available smoke tubes, the direction and approximate velocity of soil gas movement from the soil to the structure can be qualified. Other air movements can be identified during this test, such as those out of the top of hollow-core block walls, at the exterior soil line, and through various bypass paths between the substructure and upper floors or attic. These bypasses may be important in enhancing the building's "stack effect" which will increase substructure depressurization and soil gas entry. The "stack effect" results from indoor air that is warmer and therefore more buoyant than outdoor air. This causes pressure differences across the building shell at the top of the structure forcing indoor air to the outside and at the bottom of the structure drawing outside air (or soil gas) inside. Since the use of smoke does not quantify the air movement, procedures employing a hot wire anemometer are presently under evaluation. In this way, a mass flow rate of soil gas bearing radon into the building may possibly be estimated for different entry points.

Air Infiltration Leakage Area

The effective leakage area for infiltration of air between the outdoors and the building interior may be an important parameter in the selection of certain mitigation options, such as basement pressurization, heat recovery ventilation, and other ventilation techniques. As shown in Figure 8, effective leakage areas for 1) the entire structure, 2) the superstructure only, and 3) the substructure only fairly well characterize the distribution of leakage through the building shell. This is important to understanding radon distribution throughout the building and in controlling indoor radon levels. For example, the whole building equivalent leakage area (ELA) can be used with a model developed by Sherman and Grimsrud (1980) to estimate the natural or existing ventilation rate of the building for considering the installation and sizing of a heat recovery ventilator.

The ELA of the substructure ceiling and substructure floor and walls can be normalized by the substructure floor area to give a specific leakage area (SLA, in units of cm^2/m^2). The SLA can be used to compare substructures of different buildings and to help decide if additional sealing is recommended to reduce the leakage area. The SLA may also be useful as an index of substructure ventilation for the sizing of heat recovery ventilators in the substructure.

Depressurization of the entire structure is accomplished by using a blower door, located in a first floor exterior door with any accessways open to the substructure. All other exterior doors and windows are closed. The leakage of the superstructure alone is then measured by closing the accessways to the substructure, while exterior windows and doors in the substructure are opened to allow the substructure to reach atmospheric pressure. Finally, the leakage of the substructure alone can sometimes be measured by locating the fan in 1) a substructure exterior door or window, or 2) a doorway between the substructure and the superstructure. In the latter case, the fan exhausts into the

superstructure. In both cases, the superstructure exterior doors and windows are opened to allow the superstructure to reach atmospheric pressure. These tests should be made only after natural condition radon grab samples have been collected.

If basement pressurization is a possible mitigation option, the substructure surfaces requiring additional air leakage tightening can be identified. In addition, by using the depressurization fan, which must have a calibrated flow curve, the fan size necessary for pressurizing the basement to control radon levels can be estimated. For this measurement, it is preferable to operate the depressurization fan in the same way as the radon control basement pressurization fan is operated; *i.e.*, pressurizing the basement by pulling air from the superstructure and exhausting it into the substructure. In this configuration any valving action (dampers, *etc.*) between the two zones would mimic actual operating conditions. All doors and windows should be closed. A typical leakage test would be conducted over several points of pressure differential across the building shell (Appendix D3). By applying a linear regression to the flow and building shell pressure points, a linear estimate of the flow necessary to pressurize the basement to +3 Pa can be calculated. This will determine whether basement pressurization is practical and the size of the fan necessary to achieve it.

Estimates of the leakage area for the substructure ceiling and the substructure floor and walls may be computed from the following relationships (Figure 8):

$$ELA_w = ELA_p + ELA_b - 2ELA_c . \quad (1)$$

Rearranging equation (1) gives

$$ELA_c = \frac{ELA_p + ELA_b - ELA_w}{2} . \quad (2)$$

In addition,

$$ELA_f = ELA_b - ELA_c, \quad (3)$$

where:

ELA_w = whole building ELA,
ELA_p = superstructure ELA,
ELA_b = substructure ELA,
ELA_c = substructure ceiling ELA,
ELA_f = substructure basement walls/floor ELA.

It is important to note that the substructure leakage area (ELA_b) and the substructure wall/floor leakage area (ELA_f) include leakage area to the soil as well as to the outside. Data from the ELA measurements in the houses in this study are not yet available.

Subsurface or Near-surface Air Flow Communication

The degree of ventilation communication below the floor slab and near the bottom of the walls is another important diagnostic element both in understanding potential radon transport and in assessing the possible use of subslab ventilation techniques for mitigation. To determine the spatial extent of the pressure field that could result from subsurface ventilation or block wall ventilation, a high vacuum (200 cm H_2O static pressure) industrial vacuum cleaner is connected to one of the several large holes drilled through the slab or into the block walls discussed earlier (Figure 2, #6). A

micromanometer or other sensitive pressure measurement device is used to measure the direction and magnitude of the pressure difference (referenced to substructure pressure) and chemical smoke (or a modified hot wire anemometer) to determine air flow direction and approximate velocity at each each of the test holes including the vacuum hole. During this test, the vacuum is cycled on and off and measurements are taken under both conditions to account for any pre-existing pressure field or air flows without the vacuum operating. It has been observed that certain soil and gravel conditions have a longer response time to changing driving pressures; therefore, measurements should be made only after a delay of approximately 1-2 minutes from when the vacuum was switched on or off.

Often the pressure field developed at a point is less than the detection limit of the micromanometer (1 Pa), yet can be detected by carefully observing the direction of smoke movement at the hole. Those locations with the highest pressure differential and greatest air flow into the hole generally have the best connection or communication with the vacuum hole. Good communication can be due to highly permeable gravels or soils, channels or cavities in the near-substructure fill material, proximity to the vacuum hole, or - in the case of hollow-core block walls - little or no block fill material. Floors or walls that evidence good communication with the vacuum test are possible candidates for subsurface or block ventilation, except for those block walls that have numerous and inaccessible openings to the outside or inaccessible block openings to the inside. Because of the possibility of drawing large volumes of high concentration radon-laden soil gas into the structure, the vacuum exhaust should be vented to the outside during this test.

Appliance Effects

The operation of some fans and appliances, such as attic, bath and kitchen fans, clothes dryers, combustion and forced air furnaces, and whole house vacuum cleaners, may increase substructure depressurization as much as 10 to 15 Pa (Figure 2, #7). While exhaust fans and vacuum cleaners are typically operated for only short periods, the other devices may operate for sufficiently long periods to measurably increase radon entry. To measure the depressurization effect of these devices, they are cycled on and off up to 20 times while substructure-to-ambient pressure differences are measured with a micromanometer. The average difference between the on and off condition is taken to be that caused by appliance operation. The large combustion air requirements for some furnaces can cause measurable depressurization, while unbalanced forced air furnaces that have either leaky substructure return air ducts or plenums or insufficient substructure supply air usually have the most dramatic impact on substructure depressurization. Attic or ceiling exhaust fans may also cause substructure depressurization via bypasses between the two levels. While these conditions can be remedied by supplying outside combustion air, sealing duct leaks, balancing furnace delivery, or sealing attic bypasses, a radon entry problem would probably still exist if it did initially.

Soil Characterization

Measurements of near-house soil air permeability and radium content may be important in determining which, of pressurization or depressurization subsurface (or weeping tile) ventilation systems, will be more effective in controlling indoor radon levels (Figure 2, #8). Preliminary research indicates that, in highly permeable soils with low to moderate radium concentrations, subsurface pressurization may be more effective than depressurization (Turk, *et al.*, 1986). However, at this time, a detailed understanding of the relationship between permeability and radium content and the success of various mitigation measures has not been established. The value of

permeability data for selecting and designing other types of mitigation systems is unknown. However, the measurement of soil air permeability at every structure undergoing diagnosis would provide data useful in helping to understand the radon entry problem and for future research purposes.

Field measurements of soil air permeability can be made using a device described by DSMA (1983). Because the measurement technique for soil air permeability is still under development, there is little guidance available for selecting the number and location of measurement points. It has been observed in this study that soil permeabilities near the substructure (*i.e.*, at sites less than 0.5m, 1.5 ft., from the building) in backfill material are generally higher than in the surrounding undisturbed soil. But it is not known whether mitigation system interaction would be dominated by this near-structure layer. Of course, multiple measurement locations could be useful, but it requires considerable time to emplace a soil probe and conduct the measurement (30 to 60 minutes). A suggested procedure involves driving a 1.3 cm (0.5 in.) O.D., 1.0 - 1.5 m (3-5 ft) long pipe into the soil, following a pilot hole, at approximately 0.5 - 1.5 m (1.5-5 ft) distance from the structure. A cylinder of compressed air is connected to the pipe via a pressure gauge and flow meter. Based on the measured flow rate of air into the soil at a pressure difference of 250 Pa (see Appendix D2 for sample data log), the permeability can be calculated from:

$$K = 2.5 \times 10^{-7} \frac{Q}{Pr} \qquad (4)$$

where:

K = permeability (cm^2),
Q = flow rate (L/min),
P = pressure (cm of water),
r = inside radius of probe (cm).

Measurement capabilities with this field device range from approximately 10^{-8} to 10^{-4} cm^2. The range of possible soil permeabilities is shown in Table 3.

Table 3: Range of Soil Permeabilities*

Soil Type	Permeability (cm^2)
Clay	10^{-12}
Sandy clay	5×10^{-11}
Silt	5×10^{-10}
Sandy silt and gravel	5×10^{-9}
Fine sand	5×10^{-8}
Medium sand	5×10^{-6}
Gravel	5×10^{-4}

*Tuma and Abdel-Hady (1973).

At the same location as the permeability measurement, a soil grab sample should be collected (see Appendix D5). In addition, at least one 1 kilogram sample of soil should be obtained near each house from a depth at least 25 cm. This soil sample should be sent to a laboratory for analysis and determination of emanating radium.† The maximum radon concentration in soil gas for that soil can then be estimated from:

$$C_\infty = \frac{\rho e}{\epsilon} \times 10^3 \qquad (5)$$

where: C_∞ = maximum radon concentration in soil gas, (pCi/L),
ρ = soil density, (g/cm^3),
e = emanating radium concentration, (pCi/g),
ϵ = soil porosity, [cm^3 (air)/cm^3 (soil)].

2. Radon in Water

In some houses, the radon concentrations in water are high enough that radon coming out of solution can cause high indoor air radon concentrations. Previous research has estimated that the ratio of domestic water radon concentrations and indoor air concentrations is approximately 10,000 to 1 (Gesell and Pritchard, 1980; Nazaroff, et al., 1985c). Thus, a radon concentration in water of approximately 40,000 pCi/L or higher may indicate that the water is an important source of radon, contributing approximately 4 pCi/L to the indoor air concentrations.

Radon concentrations in water have a wide range. Water derived from surface or most municipal supplies do not contain sufficient dissolved radon to warrant concern. Most private well water supplies are also low in radon, however some individual wells have been found to have concentrations above 10,000 pCi/L and upwards of 10^6 pCi/L in rare cases (Nazaroff, *et al.*, 1985c). Thus testing domestic water derived from a private well is a useful diagnostic procedure.

The most direct method for determining radon levels in housewater, Figure 3, is to obtain two 1-liter samples of non-aerated water from the building supply that has not been conditioned or filtered. An outdoor faucet is a good supply location. The faucet is opened and water is allowed to flush for several minutes. Then the containers are slowly filled with a short tube directed to the bottom of the container to avoid aeration of the sample. After sealing and labeling, the containers should be sent within three days to a facility for analysis by gamma spectrometry (see Appendix D6).

Due to the cost and difficulty in locating a facility for the water sample analysis, an alternative technique is currently under study. In this procedure, the bathroom shower of hot water is operated for 15 minutes while the bathroom door is closed, large gaps and cracks to the remainder of the house and outside are sealed, and any mechanical ventilation is turned off. By using a simplified mass balance equation, a crude estimate of the radon concentration in water is possible. Assuming that the bathroom ventilation and other removal rates are negligible:

$$C(t) \approx \frac{S}{V} t + C(o) \qquad (6)$$

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†"Emanating radium" is the radium concentration times the emanating fraction, the portion of radon generated that reaches pore spaces and is available for transport.

where:

C(t) = Concentration in bathroom air at time t (pCi/L),
S = Source rate (pCi/hr),
V = Bathroom volume (liters),
t = Elapsed time of test (hr); for these purposes, t = 0.25 hr, and
C(o) = Concentration in bathroom air at t = 0 (pCi/L).

The source rate, S, is further defined as:

$$S = E C_w W \quad (7)$$

where:

E = Transfer coefficient (dimensionless); and approximately equal to 0.9 (*i.e.*, approximately 90% of radon in the water is released to the air)
C_w = Concentration in water (pCi/L), and
W = Water flow rate (liters/hr).

Substituting, Equation 1 can be solved for the radon concentration in water.

$$C_w = \frac{V (C(t) - C(o))}{EWt} \quad (8)$$

The necessary measurements for estimating the radon concentration in water are therefore: W, shower head flow rate (using a measured container and stopwatch), V, bathroom volume, C(o), grab sample of bathroom air radon concentration before shower test, and C(t), grab sample of bathroom air radon concentration after 15-minute shower operation. Once again, a calculated radon in water concentration of 40,000 pCi/L or higher suggests that treatment of the water may be necessary. Treatments can include processes that filter the water through a charcoal column or aerate the water (Becker and Lachajczyk, 1984). Alternatively, various methods of ventilation (with or without heat recovery) can be employed to control the radon in room air after it has come out of solution. After corrective action has been taken, follow-up measurements of both water and building air should be made.

3. Radon Flux from Building Materials

If indoor air radon concentrations are higher than can be reasonably explained by levels in the water (water infrequently contributes significantly to air concentrations exceeding 20 pCi/L), then action should be taken to control the dominant radon source first. It is remotely possible that the building materials contain sufficient radionuclide mineralization to result in high radon flux rates and corresponding high indoor radon concentrations. The visual inspection during the building survey (Appendix B) should identify suspected earth-based materials such as native stone, concrete, and aggregate, as well as unusual construction features incorporating local geological formations (rock outcroppings). See Figure 4.

If certain materials are judged to be potential sources or diagnostic tests do not suggest other sources in the building, then a radon flux measurement on various materials surfaces should be made (Appendix D4). In this measurement, a shallow pan containing open charcoal canisters is temporarily sealed to the surface with duct seal or a similar adhesive material for 24 to 48 hours. With this technique, it is possible to obtain very high flux measurements when the pan is attached to a porous material (concrete or cinder block) backed by high radon soil gas. This should not be

interpreted as a building materials problem; rather it may be diffusive or convective flow from high concentration radon gas in the block cells. Placing the pan on surfaces above grade should alleviate some of this difficulty, except for open cell cinder or concrete blocks that may contain high radon soil gas in the open cells even above grade. The charcoal canisters are then analyzed and a flux rate, F, computed (pCi m^2hr^{-1}). The material flux contribution to the indoor air radon levels can be estimated by once again using a steady-state form of Equation 6:

$$C = \frac{S/V}{a} \qquad (9)$$

where:

C = concentration in room (zone) air (pCi/L),
V = room (zone) volume (liters),
S = FA, and
F = radon flux rate (pCi m^2hr^{-1}),
A = material surface area (m^2),
a = ventilation rate (hr^{-1}).

Solving for the source rate necessary to produce guideline levels (4 pCi/L) of radon in the indoor air and assuming a typical ventilation rate of 0.5 air changes per hour (ACH) gives:

$$S = 2V \qquad (10)$$

or:

$$\frac{FA}{V} = 2 \text{ pCi } L^{-1}hr^{-1} \qquad (11)$$

This formulation is interpreted to mean that building material radon flux may be a problem if the normalized source rate is approximately 2 pCi $L^{-1}hr^{-1}$ or higher. Sealants, coating, or material removal may then be recommended. Follow-up measurements of flux and heating season indoor air radon concentrations would be made after any corrective action. However, as in the case of water contamination, other sources are likely to dominate and should be addressed first.

B. Summarize Test Data

Once all observations and measurements are completed, they should be compiled in a way that clarifies the predominate mechanisms of radon entry, the extent of areas of high radon concentrations in soil gas, the locations of likely entry points, and the most suitable mitigation options. One practical method of summarizing is to prepare a "map" of all the measurements as shown by the example in Figure 9. The data are referred to by letter codes.

In this example, concentrations of radon in soil grab samples are highest along the common foundation wall between the basement and the slab-on-grade. In addition, the suspect radon entry points are the forced air heating registers in the slab-on-grade and holes of unknown origin through the common foundation wall. Subslab ventilation communication is poor across the slab-on-grade because there is no gravel underlying the slab, while communication is good under the basement slab where there is gravel as shown by data obtained using the vacuum system. With this system attached to point IF7 (in the slab-on-grade area) little effect was observed at locations IW6, IW7, duct under the stairs and at the forced air registers through the slab. When the vacuum was

attached to point IF1, however, the observed pressure field (VΔP) and air movement (VT) at all basement floor holes and at many wall holes were significantly affected.

For this house, the data suggested the installation of a subsurface ventilation system at the common wall which effectively ventilates the vertical space behind the wall and the space below the basement slab near the common wall. The pressure field developed by this system was observed at the far end (west) of the basement slab. In addition, the penetrations of the common wall were sealed. These recommendations reduced average basement radon concentrations from 217 ± 46 (standard deviation) pCi/L to 3.0 ± 1.1 pCi/L and first floor concentrations from 72 ± 22 pCi/L to 2.2 ± 0.9 pCi/L. Figure 10 is a plot of the pre- and post-mitigation basement radon concentrations. The two large radon peaks occurred during installation of the system when the subsurface holes were opened through the slab and walls. These preliminary results show that by identifying the areas of highest concentration and ventilation communication, a localized system can be installed that may be more efficient and economical.

C. Selection of Mitigation Systems

This report makes a few inroads in the approach for selecting the appropriate mitigation system. Which system to select for each situation is currently based on experience, engineering judgment, and information collected during the diagnostic measurements. By using a diagnostic "map" such as the one prepared in Figure 9, selection and design of systems is facilitated since obvious entry points and high radon areas are identified.

Unfortunately, the factors and their interrelationships affecting mitigation system performance are still poorly understood. Therefore considerable ambiguity still remains regarding decisions in certain situations for selecting one type of system over another or in the sizing and placement of subsurface ventilation systems. Some situations may require an initial system installation to know if the correct decision was made, which is then followed by modifications and tests to re-evaluate system performance. These empirical experiments should improve our understanding of the fundamental mechanisms influencing radon entry and control and mitigation system performance.

As noted in the introduction, a detailed description of radon mitigation techniques is beyond the scope of this paper. The following mitigation system descriptions are keyed to the options listed in Figure 6. For a more detailed explanation of various mitigation systems, the reader is referred to general discussions in Sanchez and Henschel (1986), Fisk (1986), Ericson, *et al.*, (1984), Nitsckke, *et al.*, (1985), Sachs and Hernandez (1984), Scott and Findlay (1983), Turk, *et al.*, (1986) and the various DSMA references listed in section V.

1. Crawlspaces

As described in Figure 5, crawlspaces with high radon concentrations are generally the easiest to mitigate and should be addressed first if the diagnostic "map" indicates a radon problem. Earlier experimentation suggests that in homes where radon concentrations in occupied spaces are higher than the guideline, crawlspaces should receive mitigation if the crawlspace concentration is greater than or equal to 0.75 times the concentrations in the occupied space or if it is greater than other substructure zone concentrations. The factor of 0.75 allows for errors in measurement of zone air concentrations.

Typically, crawlspace radon can be controlled by providing additional ventilation through installing or enlarging openings cut into the exterior crawlspace walls. These

openings will increase crawlspace ventilation and reduce the amount by which crawlspaces are depressurized due to communication with the building interior. Alternatively, a fan can be used to both ventilate and overpressurize the crawlspace. Gaps and openings between the crawlspace and the living area should be sealed, including any subfloor ducts. While sealing is probably most important in blocking the entry of cold crawlspace air into the heated structure, it may also stop the entry of any residual radon that remains in the crawlspace.

It may be that radon in the crawlspace has originated in other parts of the same building and has simply been mixed into the crawlspace air by openings, gaps, leaks, or ductwork. In these situations, radon levels in the crawlspace usually are lower than in other substructure zones. It is also possible that, while the crawlspace is not the dominant source of radon, it may be a secondary source sufficient to elevate indoor levels in occupied zones above the recognized guideline. When this occurs, all substructure zones contributing to the radon problem should be mitigated.

After a mitigation system has been installed, a 14-day average indoor air radon concentration measurement should be made during the heating season. Other measurements detailed in Figure 7 should also be made. If occupied space radon levels remain high and crawlspace radon levels are high compared to other substructure zones, then additional, more efficient crawlspace ventilation is recommended. However, if crawlspace radon concentrations have been reduced to less than 0.75 times the higher-than-guideline occupied space concentrations and less than other substructure zone concentrations, then the crawlspace radon problem has probably been resolved while contributions from other substructures zones will require attention.

2. Other Substructure Types

Three other predominant substructure types are listed in Figure 5: basement with poured foundation wall, basement with block foundation wall, and slab-on-grade. There are other less frequently occurring substructure types, but the majority are a hybrid of these three, plus a crawlspace. Possible mitigation options for radon control in the appropriate substructure type are indicated by number in Figure 5; the options are described in Figure 6 along with certain qualifications as to their selection and application. More details are given in the references (DSMA, 1979, 1980; Sanchez and Henschel, 1986; Ericson, *et al.*, 1984; Fisk, 1986; Henschel and Scott, 1986; Nazaroff, *et al.*, 1981; Nitschke, *et al.*, 1985; Sachs and Hernandez, 1984; Scott and Findlay, 1983; Turk, *et al.*, 1986).

Ventilation

The mitigation systems that are considered for installation are shown on Figure 6. Options 10 and 11 are techniques for removing radon once it has entered the structure and are limited by the practical amounts of ventilation air that can be added. Therefore, these systems are useful only below certain maximum indoor radon levels. These systems are also not recommended in houses where large air infiltration leakage areas have been measured (suggesting high natural ventilation rates $\geq$1.5 ACH), since the amount of additional ventilation required for successful radon control could be prohibitive.

Subsurface Ventilation

Options 1 to 3, sump, floor drain, and French drain (floating slab) sealing are almost always recommended when these are present. Subsurface ventilation via sumps (option 3a), weeping tile (option 5), and sealed French drain ducts (option 3b) may be

useful for controlling the radon source where they can be practically employed as collection and distribution points or manifolds. Other subsurface ventilation systems (option 4) can be installed at the location of indicated radon entry points and "hot" spots to minimize the cost of extensive installations, but can also be installed to mitigate a more widespread or distributed radon problem if good subslab ventilation is possible through an existing gravel underlayment. Both subsurface pressurization and depressurization forms of subsurface ventilation have been demonstrated to be effective in some houses. However, the differences between these two methods and any potential long-term problems are not yet clearly understood, so recommendations cannot be made for selecting between the two techniques.

Block Wall Ventilation

Hollow-block wall ventilation (option 6) should probably be limited to those structures that have walls with few air leaks (gaps, cracks, holes) or with leaks that can be easily closed; and have walls with enough pathways between the block cavities for good ventilation communication.

Basement Overpressurization

Basement overpressurization (option 9) is a relatively new technique that is operating successfully in five Spokane, WA residences (Turk, *et al.*, 1986). It should still be considered an experimental technique that is to be installed in buildings with tight basements, preferably with no forced air furnace, and with no combustion appliances in upper occupied floors.

Sealing of Cracks and Holes

Sealing of cracks and holes (option 8) may be effective in improving the performance of other techniques, but may have limited impact by itself on radon levels where there are many inaccessible cracks and openings.

Mitigation techniques that were not considered as options because of lack of testing, impracticality, or ineffectiveness are: substructure surface coatings, removal of contaminated soil from around a substructure, and indoor air cleaning devices.

D. Post-mitigation System Evaluation and Optimization

Following installation of the radon control systems, observations and measurements to monitor system performance should be made (Figure 7). Measurements of temperatures, air flow rates, and differential pressures in ducts and pipes help to define the operating characteristics and efficiency of heat recovery ventilators, subsurface ventilation systems, and basement pressurization systems. Air flows are measured with a pitot tube or hot wire anemometer traverse of the duct or pipe. In addition, radon concentrations monitored by grab samples in the exhaust stream of subsurface ventilation indicate the effectiveness of removal strategies on depletion of the radon source. Periodic inspections are necessary to monitor the integrity of sealants, fillers, bonding agents; connections and physical attachments; noise and vibration of fans and blowers; accumulation of moisture and condensation; and leaks and bypasses in ducts and pipes. Discussions with building occupants and owners should also identify other system weakness such as noise, convenience, and appearance.

The mapping survey of radon grab samples, pressure differences, and air flow movement should be repeated to determine the extent of system effects on radon sources and near-substructure pressure fields. Before commencing follow-up

measurements a minimum 12-hour delay is necessary to allow stabilization of the indoor building environment. Follow-up average indoor air radon concentrations are also measured for a minimum of two days during the heating season. While this is a very short measurement period, higher-than-guideline radon levels indicate that the mitigation system is not operating properly and that further action is required. Lower-than-guideline levels are substantiated by subsequent measurements of at least 14-day duration. In general, system tuning is preferable when indoor concentrations have been reduced below 2 pCi/L since it is possible that the system is grossly overdesigned and that system complexity, energy requirements, operating costs, or noise levels can be substantially reduced. This is an iterative process involving small modifications followed by monitoring that minimize the installed system until indoor radon levels just begin to show an increase. At this point, the operating conditions of the system are returned to the next higher level of operation so that the system is not operating at the margin of failure.

If indoor radon concentrations remain above the guideline after system installation, then the follow-up grab sample survey may assist in deciding on the next step. For source control systems, the installed system is not controlling radon entry as designed if: 1) grab samples from suspected entry points are still greater than room concentrations, or 2) the pressure field at those points is insufficient (air moving out of entry point). In these cases, the system performance should be boosted by increasing pressure differences or flow rates delivered by the fan or by installing additional ventilation points (for a subsurface ventilation system) near the high radon areas and remaining uncontrolled entry points. If the grab samples are less than or equal to room air concentrations, and if flow and pressure measurements indicate a suitably developed pressure field, then more attention should be directed to radon entering from other substructures in the building. Alternatively, the installation of a completely different type of radon control system may be necessary.

After the 2-day measurements indicate that indoor radon levels are successfully reduced to below the guideline, a longer 14-day average measurement of room air concentrations during the heating season should be conducted. If indoor levels measured during this period are once again higher than guidelines, additional mitigation should be undertaken either in the form of modifications to existing systems, installation of alternative systems, or addressing other substructures within the building. Long-term radon levels below the guideline suggest that the system is operating successfully. However, the building owners and occupants should perform periodic system maintenance (oiling bearings, changing filters, *etc.*) and conduct long-term (one month minimum) follow-up indoor air radon concentration measurements annually during the heating season.

E. Application of Procedures in 14 New Jersey Houses

At the writing of this report, the diagnostic procedures are currently being used to select appropriate radon abatement measures in 12 of the 14 houses in the LBL/Oak Ridge/Princeton research project. Modifications to these procedures are being evaluated and will be applied to the two remaining control homes near the conclusion of the project. Maps of the type in Figure 9 have been, or are being, prepared for each of the 12 homes and mitigation systems installed in at least eight of the homes.

Preliminary data from the first three homes that have been mitigated indicate that the diagnostic procedures provided information necessary to installing localized and successful subsurface ventilation systems (see Figure 10).

IV. SUMMARY

A preliminary set of diagnostic procedures has been developed for identifying the sources of indoor radon problems and selecting systems for controlling radon. In the homes where the recommended remedial measures have been installed, based on the diagnostic measurements, radon concentrations have fallen below the guideline of 4 pCi/L. However, a rigorous process for selecting successful, optimized systems has not yet been developed for widespread use by technicians and contractors.

Three new, and largely unvalidated, techniques are presented that may assist in determining the contributions to indoor radon levels from the domestic water supply and building materials and the approximate distribution of air infiltration leakage area in a structure. This document reports progress in research still underway. Additional data and observations are being made that may support, augment, or in some cases invalidate, some of the conclusions discussed here.

Other diagnostic techniques and tools under investigation in this and other studies include: use of tracer gases to quantify entrainment of building air into subsurface ventilation systems; creating flow and pressure maps for hollow block foundation walls; attempting to quantify and apportion subsurface ventilation from below slabs and from within block walls; estimating outside air ventilation that enters along the soil/house line; and development of a radon "sniffer" with faster recovery time between samples taken from test holes, entry points, and indoor air. Another new method will attempt to challenge an installed mitigation system by using a depressurization fan to gradually increase substructure depressurization and thereby determine the system failure point.

V. REFERENCES

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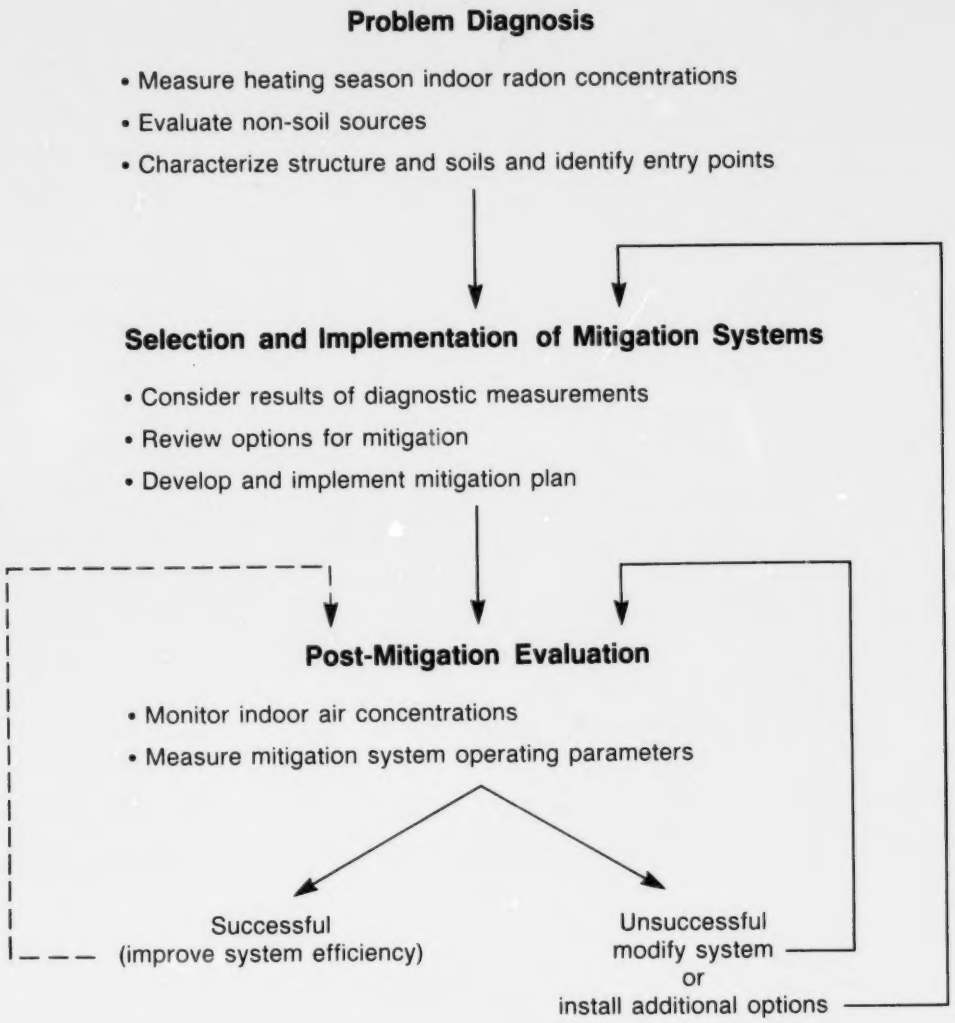
Figure 1

General Plan for Radon Control

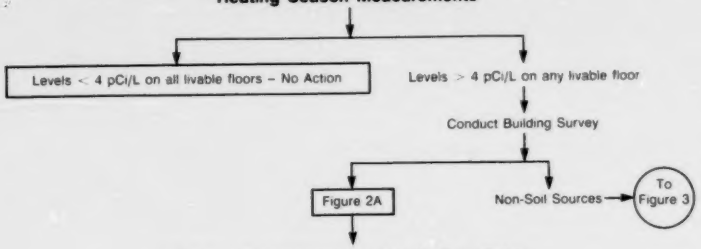

Problem Diagnosis
• Measure heating season indoor radon concentrations
• Evaluate non-soil sources
• Characterize structure and soils and identify entry points
Selection and Implementation of Mitigation Systems
• Consider results of diagnostic measurements
• Review options for mitigation
• Develop and implement mitigation plan
Post-Mitigation Evaluation
• Monitor indoor air concentrations
• Measure mitigation system operating parameters
Successful
(improve system efficiency)
Unsuccessful
modify system
or
install additional options

XBL 871-8920

Figure 2

Problem Diagnosis

Replicated, 7-Day Average Radon Concentration in Indoor Air
Heating Season Measurements



Characterize Structure and Identify Entry Points

1.) **Conduct Visual Inspection:**
- Complete forms (site and floor plans, elevations, housing surveys, occupant questionnaire)
- Probe likely entry points (wall or floor cracks and holes, masonry interface, block wall top and holes) using stiff wire, screwdriver, and smoke tubes.

2.) **Grab Sample Indoor Air under Natural Conditions**

Collect alpha scintillation cell grab samples under existing natural conditions from each unique building zone (garage, 2nd floor, 1st floor, basement, crawlspace, slab-on-grade areas).

3.) **Grab Sample Indoor Air under Mechanical Depressurization**

Collect grab samples using alpha scintillation cells from likely entry points and various building zones (this sampling could be repeated 2-3 days after the first sampling to document the variability in the technique due to environmental factors or sampling procedure)

Depressurize house using blower door to -10 Pa in substructure for > 30 min. (may not cause representative distribution of Rn throughout house)

a) grab sample of indoor air from each separately defined room or zone at mid-height

b) grab sample from cavities in bottom course of blocks approx. every 3 m (10 ft.) (through existing or 0.6 cm (1/4 in.) drilled inspection holes – fill holes on completion)

grab sample from 2 to 4 holes through slab (through existing or 1 cm (3/8 in.) drilled inspection holes)

c) grab sample from behind firred walls every 3 m (10 ft.) (Approx 15 cm (6 in.) above floor)

d) grab sample from each obvious penetration to soil (condensate drains, floor drains, sumps, service penetrations, toilet and shower bases)

e) grab sample from wall/floor joints from each wall (where accessible)

f) grab sample from representative wall and floor cracks and French drain cavities

For e) and f), either:

1) Tape over joint, crack or French drain for approximately 60 cm (2 ft.) to either side of sample location and seal ends in French drain, or

2) Tape or seal with sealant, plastic film over joint/crack, evacuate from beneath film, and allow film space to charge with soil gas before collecting sample.

h) grab sample from other confined space in contact with the walls or floor, such as framed wall cavities

Count the activity for each sample (see text) and identify on house floor plan. Samples with concentrations ≤ room concentration are not likely entry points, those with concentrations ~ 2-3 X room concentration are possible entry points, and those with concentrations > 3 X room concentration are likely entry points.

4.) **Qualify Air Movement From Likely Entry Points:**

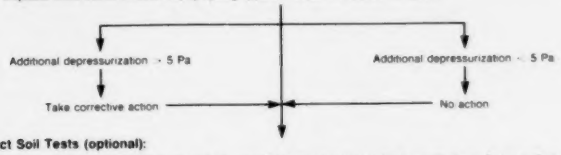
Depressurize house to ~30 Pa in substructure to characterize air movement from soil to house through entry points using Chemical smoke

Check flow at: substructure cracks, holes or joints in slabs or walls
tops of block walls
previously drilled test holes
between floors
exterior soil line
other potential entry points: sumps, drains, shower and toilet bases, service entrances and penetrations

5.) **Conduct Blower Door Tests to:**
- measure the equivalent leakage area of: • the whole house • substructure only • superstructure only
- identify large holes and bypasses between upper floors and basements that will enhance the stack effect

6.) **Observe Ventilation Communication Within Block Walls and Beneath Slabs:**
- using high vacuum (2 in. 80 in. water) and high flow (170 m^3h^{-1}, 100 cfm) blower, depressurize subslab region and measure pressure drops and determine air movement at likely entry points and drilled test holes, including those in walls.
- attach blower to block walls and check for air leaks in the walls and the extent of the induced ventilation at cracks and holes and drilled test holes.

7.) **Observe Effect of Appliance Operation:**
- using micromanometer determine additional depressurization of substructure due to appliance operation (dryer, furnace imbalance, fireplace, wood stove, exhaust fan) by cycling appliance on/off for approx. 20 cycles

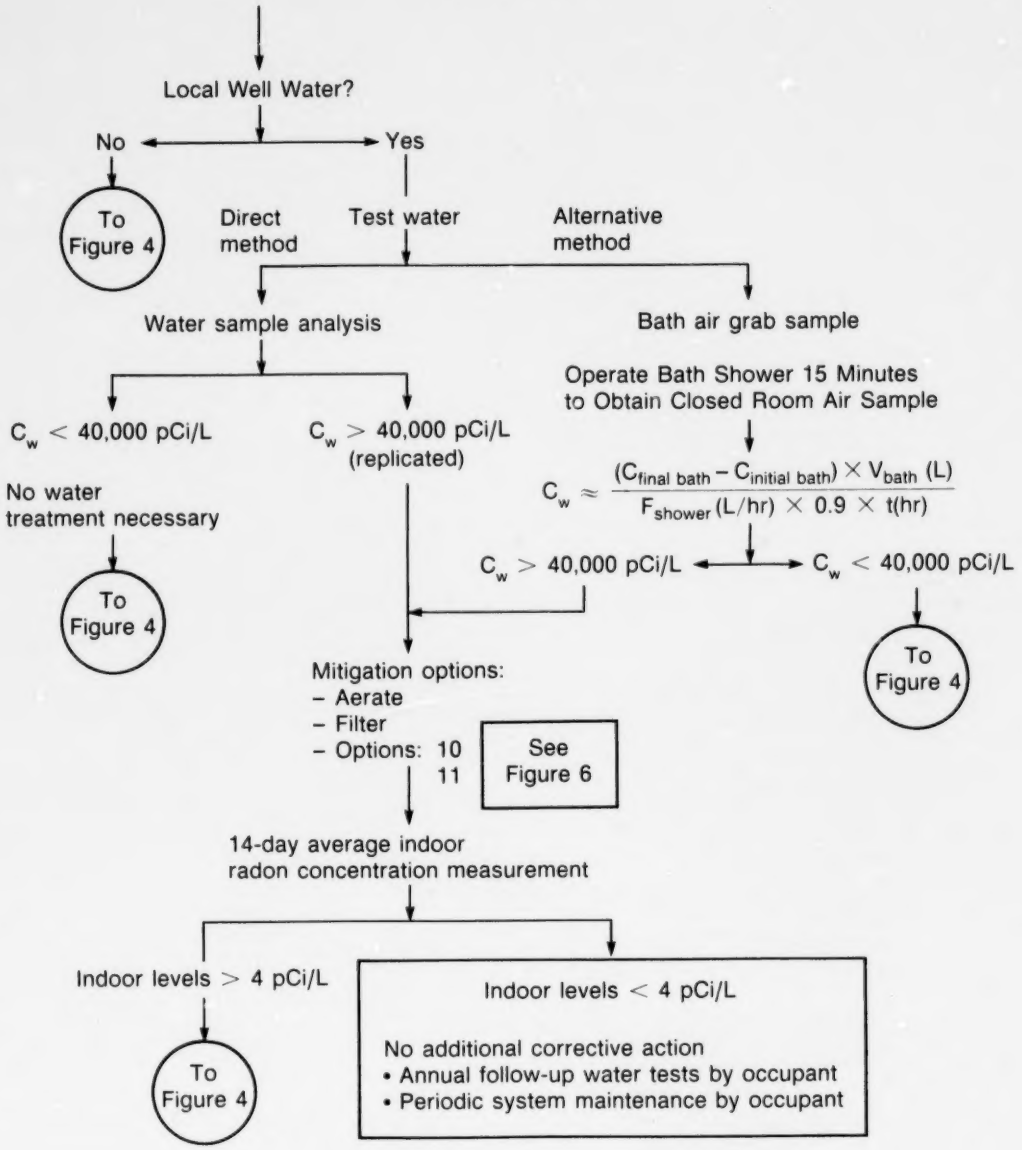


8.) **Conduct Soil Tests (optional):**
- if Subsurface or weeping tile ventilation may be considered as mitigation options, conduct near-house soil air permeability test, and soil Ra test.

XBL 871 8919

Figure 3

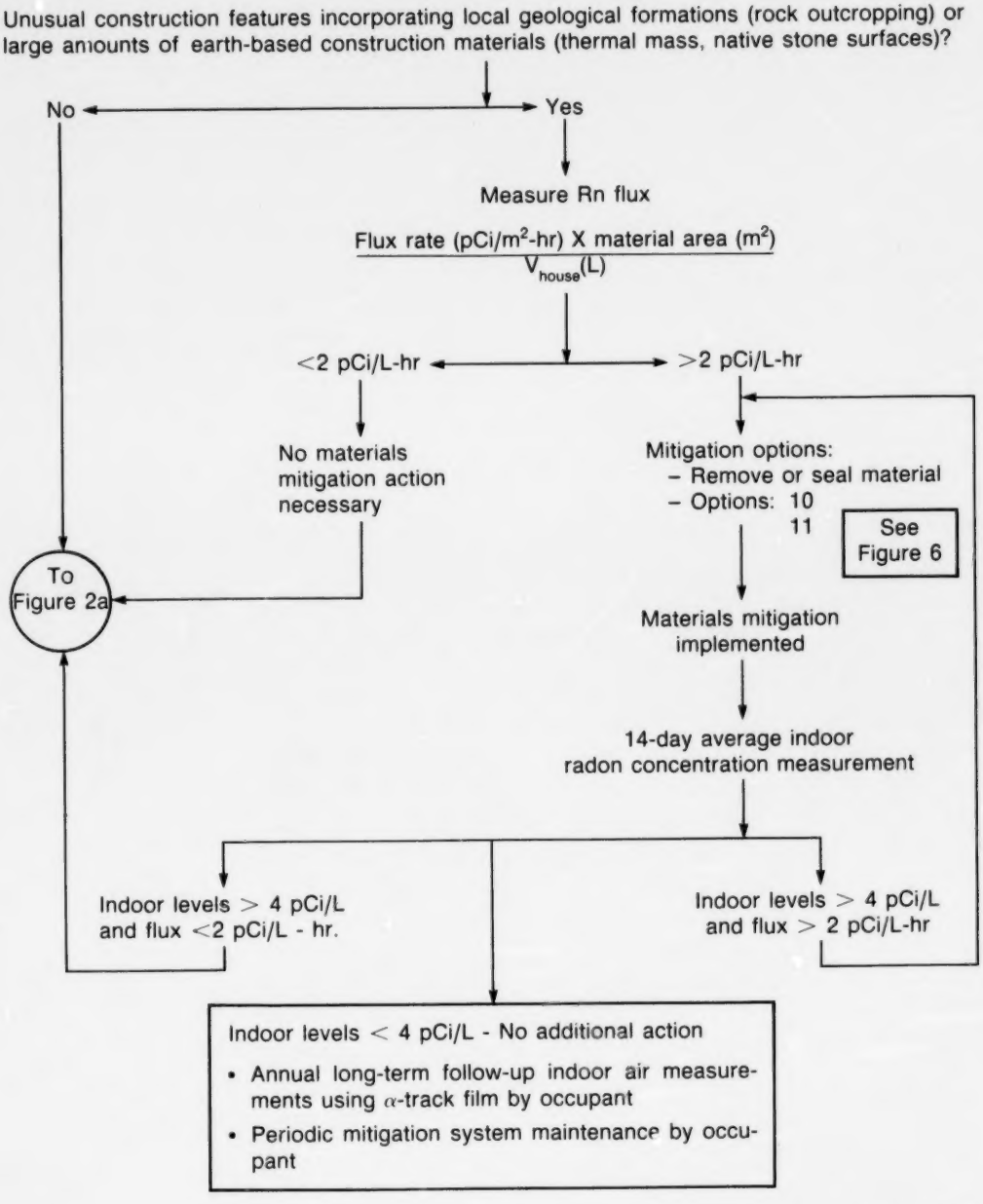
Radon in Water



XBL 871-8917

Figure 4

Radon Flux from Building Materials


Unusual construction features incorporating local geological formations (rock outcropping) or large amounts of earth-based construction materials (thermal mass, native stone surfaces)?
No
Yes
Measure Rn flux
Flux rate (pCi/m²-hr) X material area (m²) / V house (L)
<2 pCi/L-hr
>2 pCi/L-hr
No materials mitigation action necessary
Mitigation options:
– Remove or seal material
– Options: 10
11
See Figure 6
To Figure 2a
Materials mitigation implemented
14-day average indoor radon concentration measurement
Indoor levels > 4 pCi/L and flux <2 pCi/L - hr.
Indoor levels > 4 pCi/L and flux > 2 pCi/L-hr
Indoor levels < 4 pCi/L - No additional action
• Annual long-term follow-up indoor air measurements using α-track film by occupant
• Periodic mitigation system maintenance by occupant

XBL 871-8918

Figure 5

Selection of Mitigation Systems

After a careful review of the substructure(s), itemization of potential entry points, grab sample and air flow mapping, and occupant comments on operation of certain appliances, a mitigation plan should be developed. It should address control of radon for each house starting with one substructure type before moving to the next substructure type. Crawlspaces (if they exist) are typically the simplest type to mitigate and work should begin here if the diagnosis so indicates.

Crawlspace

No

Other predominant substructure types or combinations

Basement With Poured Foundation Walls

As indicated by mapping and inspection survey.

Mitigation options: 1, 2, 3, 4, 5, 7, 9, 10, 11

See Figure 6

Basement With Block Foundation Walls

As indicated by mapping and inspection survey.

Mitigation options: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

See Figure 6

Slab on Grade

As indicated by mapping and inspection survey.

Mitigation options:

4 In addition, subslab heating system ducting may require sealing from occupied spaces and rerouting through attic.

5 In addition, subslab heating system ducting may require sealing from occupied space and rerouting through attic.

7

10

See Figure 6

To Figure 7

Yes

Crawlspace concentration < 0.75 x occupied space – and less than other substructure zone concentrations

Crawlspace concentration ≥ 0.75 x occupied space concentration or greater than other substructure zone concentrations

Install 0.09 m^2 (1 ft^2) uniformly distributed ventilation/9 m^2 (100 ft^2) floor area or install fan sized for 5 ACH to overpressurize to ~10 Pa. Install thermal insulation. Seal between crawlspace and structure, including return air ducts.

14-day average indoor radon concentration measurement

Indoor levels > 4 pCi/L

– Additional mitigation

Indoor levels < 4 pCi/l - No additional action

- Annual long-term follow-up indoor air measurements using α-track film by occupant
- Periodic mitigation system maintenance by occupant

XBL 871-8915

Figure 6

Mitigation Options

1) Sump sealing – active and inactive sumps
2) Floor drain sealing – if not water-trapped
3) a) Sump sealing and ventilation – active or inactive sumps with or without drain tile
   b) French drain sealing and ventilation
4) Subsurface ventilation

A) Exterior	B) Interior
• If homeowner prefers exterior	Gravel under floor slab
• No landscaping interference	• Central ventilation point every 45 m^2 (500 ft^2)
• No utilities interference	No gravel
• Perimeter wall entry points	• Locate near entry points

Exhaust ventilation – soil impermeable, soil Ra high
Supply ventilation – soil permeable, soil Ra low

Drill series of small inspection holes in floor (1 cm; 3/8 in. diam.) and walls (0.6 cm; 1/4 in. diam.) to determine extent of pressure field.

5) Weeping tile ventilation
   • Where tile is accessible
   • Where tile is proximate to entry points
6) Wall ventilation – only if sealing successfully limits fan size to $< 500\ m^3h^{-1}$ (300 cfm) (smoke tubes at inspection holes to verify extent of ventilation)
7) Floor crack sealing
   • Where majority of cracks accessible
   • Where cracks localized – no network of cracks
   • Floating slab gap if no indication of water entry
8) Wall cracks and hole sealing
   • Where majority of openings are accessible
   • Where openings are localized
   • Only if blocks are open cell
9) Basement overpressurization (special option)
   • Where leakage of basement membrane is small
   • Where sealing of exterior and interior membranes is possible
   • Where if heating system is forced air, ductwork is tight and no forced air furnace registers present in basement
   • Where 1st floor vented combustion devices are not present

   Use blower door on basement to estimate approximate fan size: should be < 1 ACH delivery to achieve 5 Pa over-pressure
10) Balanced ventilation with heat recovery (special option)

    Multiple substructures:

    • If indoor concentrations > 4 pCi/L, < 20 pCi/L on all floors:
      – Ventilate all floors with 5 X original ventilation to < 2 ACH (new total)

    Basement only:

    • If basement concentrations < 80 pCi/L
      – Ventilate only basement where original basement ventilation < 0.2 ACH to new total < 3.5 ACH
    • System must be installed to match existing finish
11) Balanced ventilation w/out heat recovery (special option)
    • Unoccupied basements sealed and thermally insulated from occupied space.
    • In basement install 0.09 m^2 (1 ft^2) uniformly distributed vents to the outside per 4.6 m^2 (50 ft^2) floor area or install fan sized to 5 ACH to overpressurize substructure to 10 Pa

Options not considered here : Coatings
Soil removal
Air cleaning

Figure 7

Post-Mitigation Evaluation

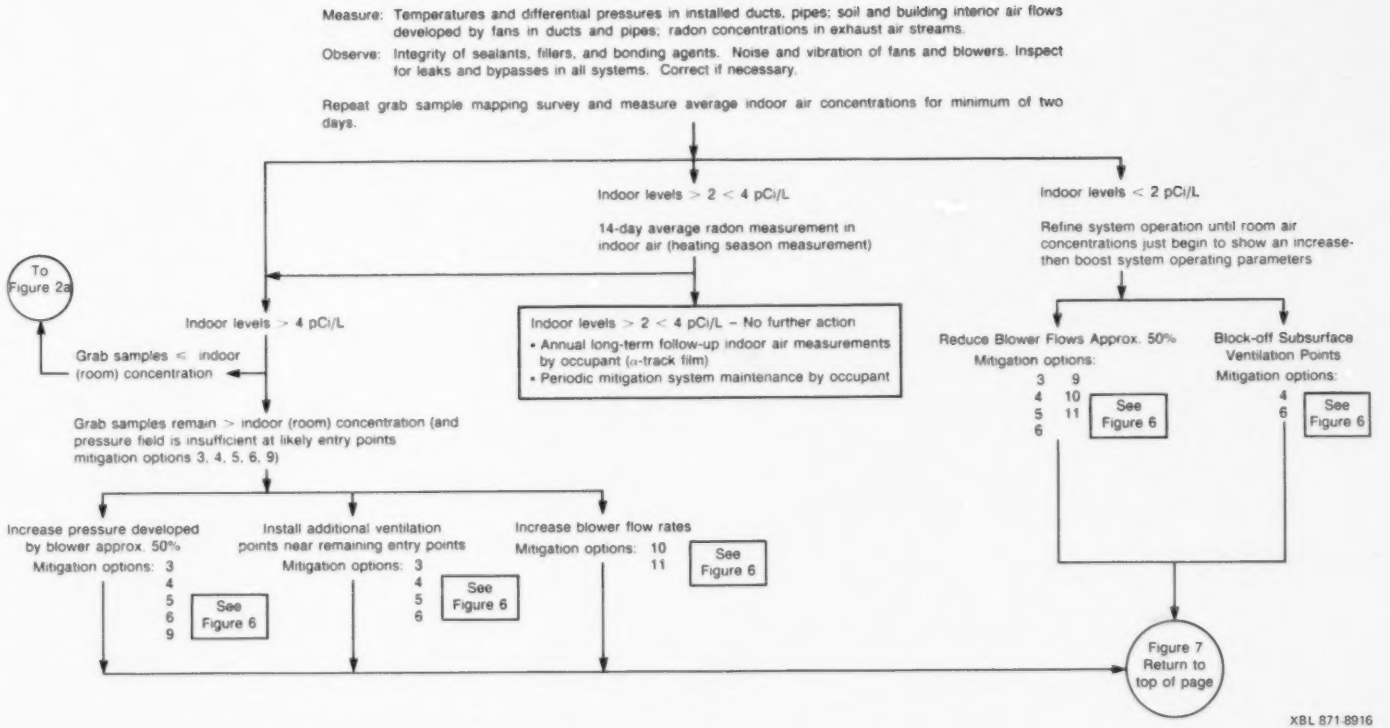
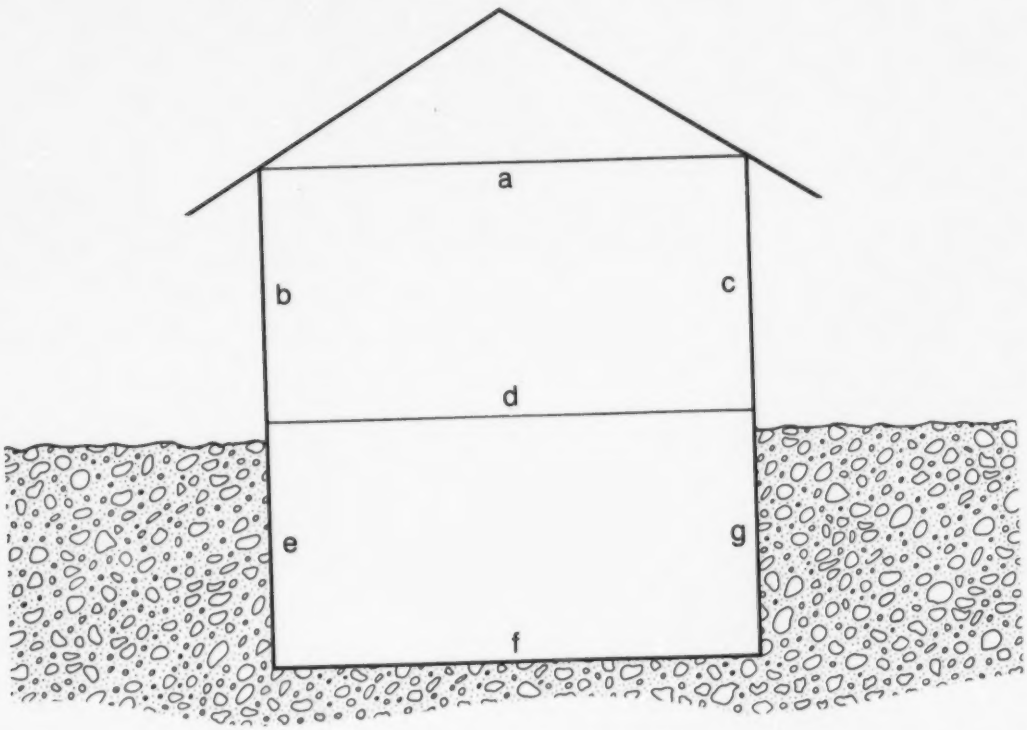


Figure 8

Distribution of Structure Effective Leakage Areas



Whole building (ELA_w) = a + b + c + e + f + g

Superstructure (ELA_p) = a + b + c + d

Substructure (ELA_b) = d + e + f + g

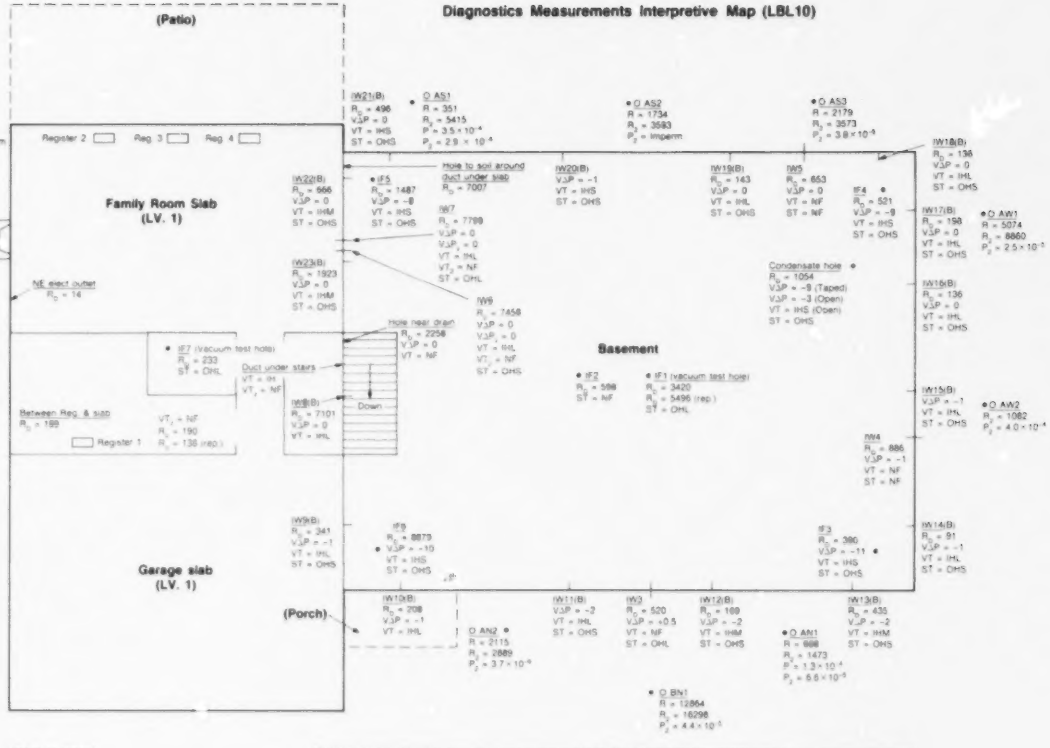
Substructure ceiling (ELA_c) = d

Substructure walls/floor (ELA_f) = e + f + g

XBL 871 8921

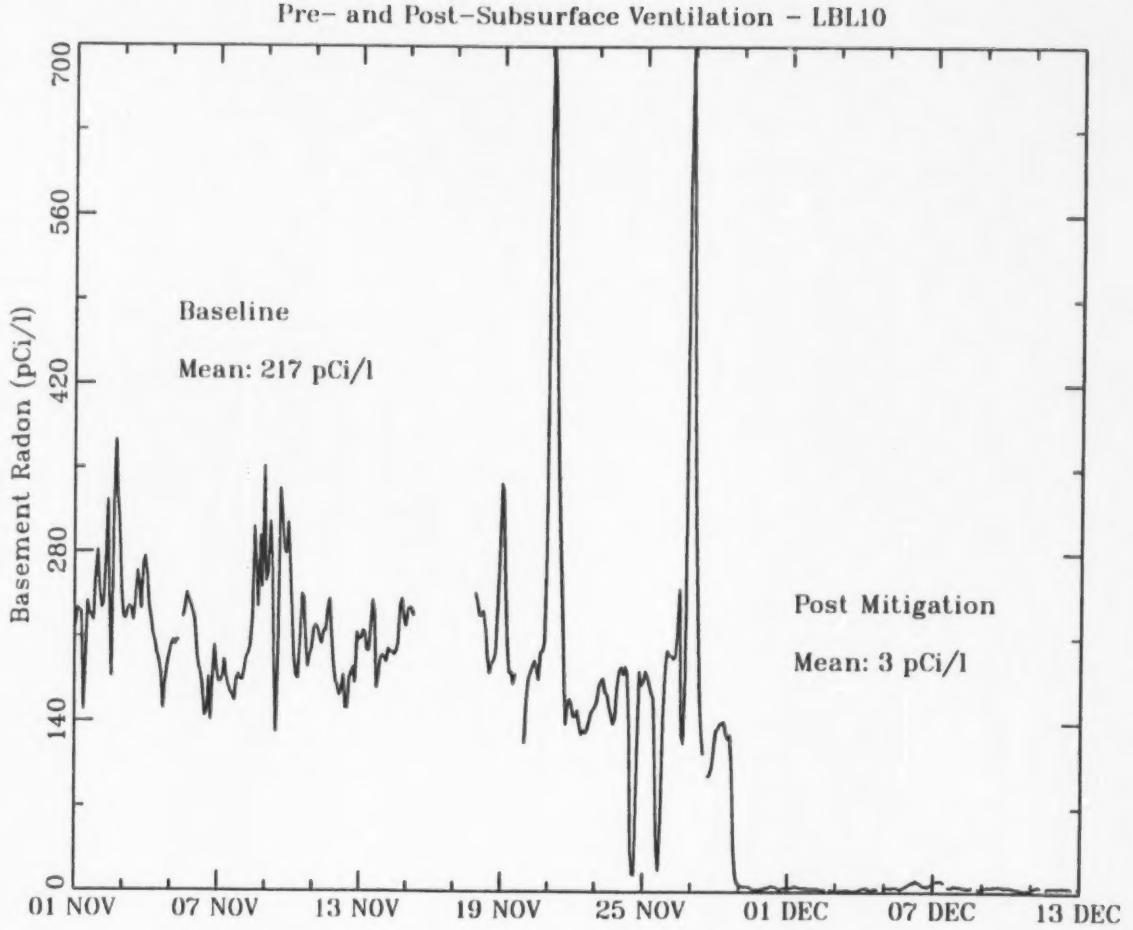
Figure 9

Diagnostics Measurements Interpretive Map (LBL10)



XBL 871-8914

FIGURE 10



XBL 873-1361

RADON DIAGNOSTIC CHECKLIST

NAME _____ HOUSE ID _____

DATE _____

NON-SOILS: [] Water Sample From Outside Faucet _____

[] Surface Flux Measurements: [] Wall _____

[] Floor _____

SOILS: [] Soil Air Permeability _____

[] Soil Gas Grab Samples _____

[] Core Sample _____

BUILDING STRUCTURE: [] Visual Inspection, Complete Survey Form

[] Natural Condition Scintillation Cell Grab Samples

[] Level 2 _____

[] Level 1 _____

[] Level 0; Each Unique Zone _____

_____

[] Ambient Air Sample; Outside Air Temp _____

Wind Speed _____

Inside Air Temp _____

[] Closed Bathroom, 15 Min. Shower Operation _____

[] Drill Test Holes in Floors/Walls

[] Start Data Logging on 1 Min. Interval:

[] Synchronize All Clocks

[] Shut Off Combustion Appliances

[] Mechanical Depressurization

[] Scintillation Cell Grab Samples (to - 10Pa)

[] Substructure Firred Wall Cavities _____

[] Substructure Block Wall Cells _____

[] Substructure Wall, Floor Cracks _____

[] Substructure Service Penetrations _____

[] Substructure Test Holes _____

[] Natural Condition Sample Locations _____

[] Air Movement Smoke Tube (to - 30 PA)

[] Substructure Cracks, Holes (Particularly Walls)

[] Tops of Block Walls _____

[] Test Holes

[] Exterior Soil Line _____

[] Between Floors

[] Other

[] ELA Tests:

[] Whole House (Open to Substructure)

[] Substructure Only _____

[] Super Structure Only _____

[] 2 Blower Test _____

[] Depressurize Attic: With [] Calibrated Blower

[] Whole House Attic Fan

[] Cycle Fan and Measure Basement ΔP _____

[] Appliance Cycling - Substructure ΔP Measurements as Appliances are Cycled On/Off 5 Times

[] Clothes Dryer _____

[] Exhaust Fans _____

[] Furnace: [] Combustion Air Only _____

[] Fan Only _____

[] Both of Above _____

[] Whole House Vacuum Cleaner _____

[] Jenn-Air

OTHER MEASUREMENTS: [] Sub-Slab ΔP Mapping With Industrial Vacuum

[] Through Floor _____

[] Through Walls _____

Optional [] Soil Line SF_6 Injection While Depressurized:

Use Miran to Sample: [] Substructure Room Air _____

[] Block Wall Cells _____

OTHER TASKS: _____

_____

_____

_____

RADON SOURCE DIAGNOSIS
BUILDING SURVEY

NAME: _____ HOUSE INSPECTED _____

ADDRESS: _____ DATE _____

_____

_____ ARRIVAL TIME _____

PHONE NO: _____ DEPARTURE TIME _____

SURVEY TECHNICIANS: _____

_____

_____

_____

I. BASIC CHARACTERIZATION OF BUILDING AND SUBSTRUCTURE

Site

1. Age of house _____
2. Basic Building Construction:
   Exterior Materials _____
   _____
   Interior Materials _____
   _____
3. Earth-based building materials in the building - describe:
   _____
   _____
4. Domestic water source:
   a. municipal surface
   b. municipal well
   c. on-site well
   d. other _____
5. Building infiltration or mechanical ventilation rate:
   a. building shell - leaky, moderate, tight
   b. weatherization - caulk, weatherstrip, etc.
   c building exposure a. heavy forest _____
   b. lightly-wooded or other nearby buildings _____
   c. open terrain, no buildings nearby _____
   - exhaust fans: a. whole house attic fans _____
   b. kitchen fans _____
   c. bath fans _____
   d. other _____
   e. frequency of use _____
   - other mechanical ventilation _____

6. Existing Radon Mitigation Measures
   Type _____
   Where _____
   When _____

7. Locale - Description: _____
   _____

8. Unusual outdoor activities: farm _____
   construction _____
   factories _____
   heavy traffic _____

Substructure

1. Full basement (basement extends beneath entire house)
2. Full crawlspace (crawlspace extends beneath entire house)
3. Full slab on grade (slab extends beneath entire house)
4. House elevated above ground on piers
5. Combination basement and crawlspace (% of each)
6. Combination basement and slab on grade (% of each)
7. Combination crawlspace and slab on grade (% of each)
8. Combination crawlspace, basement, and slab on grade (% of each)
9. Other -- specify

Occupants

1. Number of occupants _____ Number of Children _____
2. Number of smokers _____ Type of smoking _____
   and frequency _____

Air Quality

1. Complaints about the air (stuffiness, odors, respiratory problems, watery eyes, dampness, etc.)

2. Are there any indications of moisture problems, humidity or condensation (water marks, molds, condensation, etc.)?
   _____
   When _____
   _____

Note: complete floorplan with approximate dimensions and attach.

II. BUILDINGS WITH FULL OR PARTIAL BASEMENTS

1. Basement usage: occupied, recreation, storage, other _____

2. Basement walls constructed of:
   a. hollow block (concrete, cinder)
   b. block plenums: filled, unfilled
      top block filled or solid: yes, no
   c. solid block (concrete, cinder)
   d. condition of block mortar joints: (good, medium, poor)
   e. poured concrete
   f. other materials -- specify: _____
   g. estimate length and width of unplanned cracks: _____
   h. interior wall coatings: paint, sealant, other: _____
   i. exterior wall coating: parget, sealant, insulation (type _____)

3. Basement finish:
   a. completely unfinished basement, walls and floor have not been covered with paneling, carpet, tile, etc.:
   _____
   b. fully finished basement - specify finish materials:
   _____
   c. partially finished basement -- specify:
   _____

4. Basement floor materials:
   a. contains unpaved section (i.e., exposed soil) -- specify site and location of unpaved area(s):
   _____
   b. poured concrete gravel layer underneath
   c. block, brick, or stone - specify _____
   d. other materials - specify _____
   e. describe floor cracks and holes through basement floor
   _____
   f. floor covering - specify _____

5. Basement floor depth below grade - front _____ rear_____ side 1 _____side 2_____

6. Basement access:
   a. door to first floor of house
   b. door to garage
   c. door to outside
   d. other - specify _____

7. Door between basement and first floor is:
   a. normally or frequently open
   b. normally closed

8. Condition of door seal between basement and first floor - describe (leaky, tight, etc.):
   _____

9. Basement window(s) -- specify:
   a. number of windows _____
   b. type: _____
   c. condition: _____
   d. total area: _____

10. Basement wall-to-floor joint
   a. estimate total length and average width of joint: _____
   b. indicate if filled or sealed with a gasket of rubber, styrofoam, or other materials - specify materials: _____
   c. accessibility - describe: _____

11. Basement floor drain:
   a. standard drain(s) - location: _____
   b. french drain - describe length, width, depth
   _____
   c. other specify: _____
   d. connects to a weeping (drainage) tile system beneath floor - specify source of information (visual inspection, homeowner comment, building plan, other):
   _____
   e. connects to a sump
   f. connects to a sanitary sewer
   g. contains a water trap
   h. floor drain water trap is full of water:
      a. at time of inspection
      b. always
      c. usually
      d. infrequently
      e. insufficient information for answer
      f. specify source of information:
      _____

12. Basement sump(s) (other than above): location: _____
   a. connected to weeping (drainage) tile system beneath basement floor -- specify source of information:
   _____
   b. water trap is present between sump and weeping (drainage) tile system -- specify source of information:
   _____
   c. wall or floor of sump contains no bottom, cracks or other penetrations to soil -- describe:
   _____
   d. joint or other leakage path is present at junction between sump and basement floor - describe
   _____
   e. sump contains water:
      a. at time of inspection
      b. always
      c. usually
      d. infrequently
      e. insufficient information for answer
      f. specify source of information:
      _____

g. pipe or opening through which water enters sump is occluded by water:
   a. at time of inspection
   b. always
   c. usually
   d. infrequently
   e. insufficient information for answer
   f. specify source of information:

   _____

f. Contains functioning sump pump: _____

13. Forced air heating system ductwork: condition or seal - describe: supply air: _____
    - basement heated: a. intentionally return air: _____
      b. incidentally

14. Basement electrical service:
    a. electrical outlets -- number _____ (surface or recessed)
    b. breaker/fuse box -- location _____

15. Penetrations between basement and first floor:
    a. plumbing: _____
    b. electrical: _____
    c. ductwork: _____
    d. other: _____

16. Bypasses or chases to attic (describe location and size):

    _____

17. Floor material type, accessibility to flooring, etc.

    _____

18. Is caulking or sealing of holes and openings between substructure and upper floors possible from:
    a. basement
    b. living area

III. BUILDINGS WITH FULL OR PARTIAL CRAWLSPACES

1. Crawlspace usage: storage, other _____

2. Crawlspace walls constructed of:
   a. hollow block (concrete, cinder)
      block plenums: filled, unfilled
      top blocks filled: yes, no
   b. solid block (concrete, cinder)
   c. condition of mortar joints: (good, medium, poor)
   d. poured concrete
   e. other _____
   f. estimate length and width of unplanned cracks _____
   g. interior wall coatings: paint, sealant, other _____
   h. exterior wall coating: parget, sealant, insulation (type _____)

3. Crawlspace floor materials
   a. open soil
   b. poured concrete
      gravel layer underneath
   c. block, brick, or stone - specify _____
   d. plastic sheet
      condition: _____
   e. other materials - specify: _____
   f. describe floor cracks and holes through crawlspace floor _____
   g. floor covering - specify: _____

4. Crawlspace floor depth below grade _____ _____

5. Describe crawlspace access _____
   condition _____

6. Crawlspace vents:
   a. number _____
   b. location _____
   c. cross-sectional area _____
   d. obstruction of vents (soil, plants, snow, intentional) _____

7. Crawlspace wall-to-floor joint:
   a. estimate length and width of crack _____
   b. indicate if sealed with gases of rubber, styrofoam, other - specify _____
   c. accessibility - describe _____

8. Crawlspace contains:
   a. standard drain(s) - location _____
   b. french drain - describe length, width, depth _____
   c. sump
   d. connect to: weeping tile system _____
      a. sanitary sewer
      b. water trap (trap filled, empty)

9. Forced air heating system ductwork: condition and seal - describe _____

10. Crawlspace heated: a. intentionally
b. incidentally

11. Crawlspace electrical service:
a. electrical outlets - number _____
b. breaker/fuse box - location _____

12. Describe the interface between crawlspace, basement, and slab.
_____
_____

13. Penetrations between crawlspace and first floor:
a. plumbing: _____
b. electrical: _____
c. ductwork: _____
d. other: _____

14. Bypasses or chases to attic:
_____

15. Caulking feasible from: a. basement
b. living room

IV. BUILDINGS WITH FULL OR PARTIAL SLAB FLOORS

1. Slab usage: occupied, recreation, storage, other: _____

2. Slab room(s) finish:
   a. completely unfinished, walls and floor have not been covered with paneling, carpet, tile, etc.
   _____
   b. fully finished - specify finish materials _____
   c. partially finished - specify _____

3. Slab floor materials:
   a. poured concrete
   b. block, brick, or stone - specify _____
   c. other materials - specify _____
   d. fill materials under slab: sand, gravel, packed soil, unknown _____
   - source of information _____
   e. describe floor cracks and holes through slab floor: _____
   f. floor covering - specify _____

4. Elevation of slab relative to surrounding soil (e.g., on grade, 6" above grade, etc.):
   _____
   - Is slab perimeter insulated or covered: yes, no

5. Slab area access to remainder of house - describe _____
   - normally: open, closed

6. Slab wall-to-floor joint:
   a. estimate length and width if crack _____
   b. indicate if sealed with gasket of rubber, styrofoam, other - specify _____
   c. accessibility - describe _____

7. Slab drainage:
   a. floor drain - describe _____
   b. drain tile system beneath slab or around perimeter - describe _____
   c. source of information _____

8. Forced air heating system ductwork:
   a. above slab condition and seal - describe _____
   b. below slab: _____
      a. length and location _____
      b. materials _____

9. Slab area electrical service:
   a. electrical outlets - number _____
   b. breaker/fuse box - location _____

10. Describe the interface between slab, basement, and crawlspace:
    _____

11. Penetrations between slab area and occupied zones:
    a. plumbing _____
    b. electrical _____
    c. ductwork _____
    d. other _____

12. Bypasses or chases to attic: _____

V. SUBSTRUCTURE SERVICE HOLES AND PENETRATIONS

(Note on floor plan)

Complete table to describe all service penetrations (i.e., pipes on conduit for water, gas electricity, or sewer) through substructure floors and walls. Indicate on floor plan.

Description of service, size location, accessibility	Size of crack or gap around service and type and condition of seal
Example: water, 3/4" copper pipe, through floor, accessible.	Example: Approx. 1/8" gap around circumference of pipe with sealing styrofoam gasket.

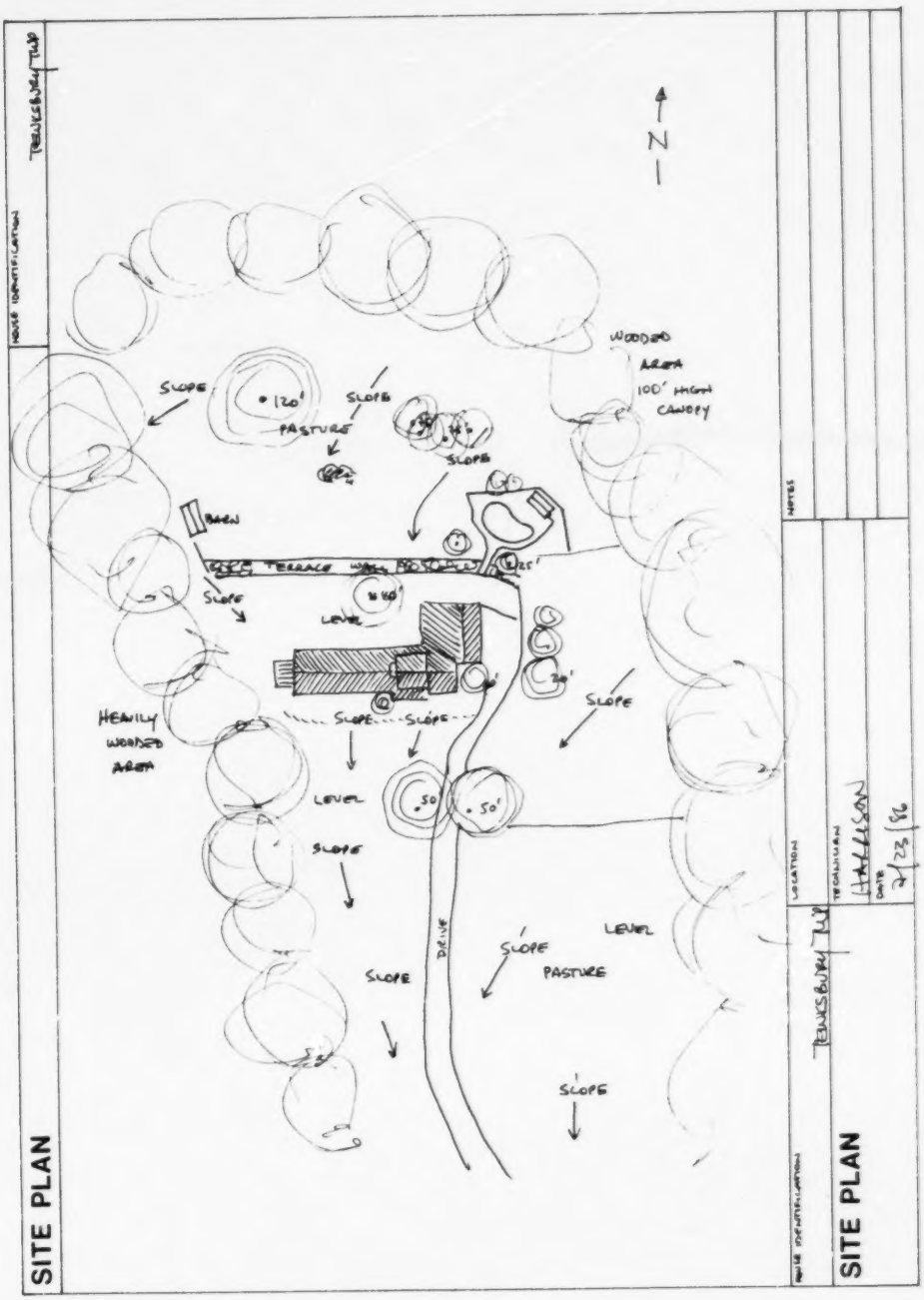
VI. Appliances

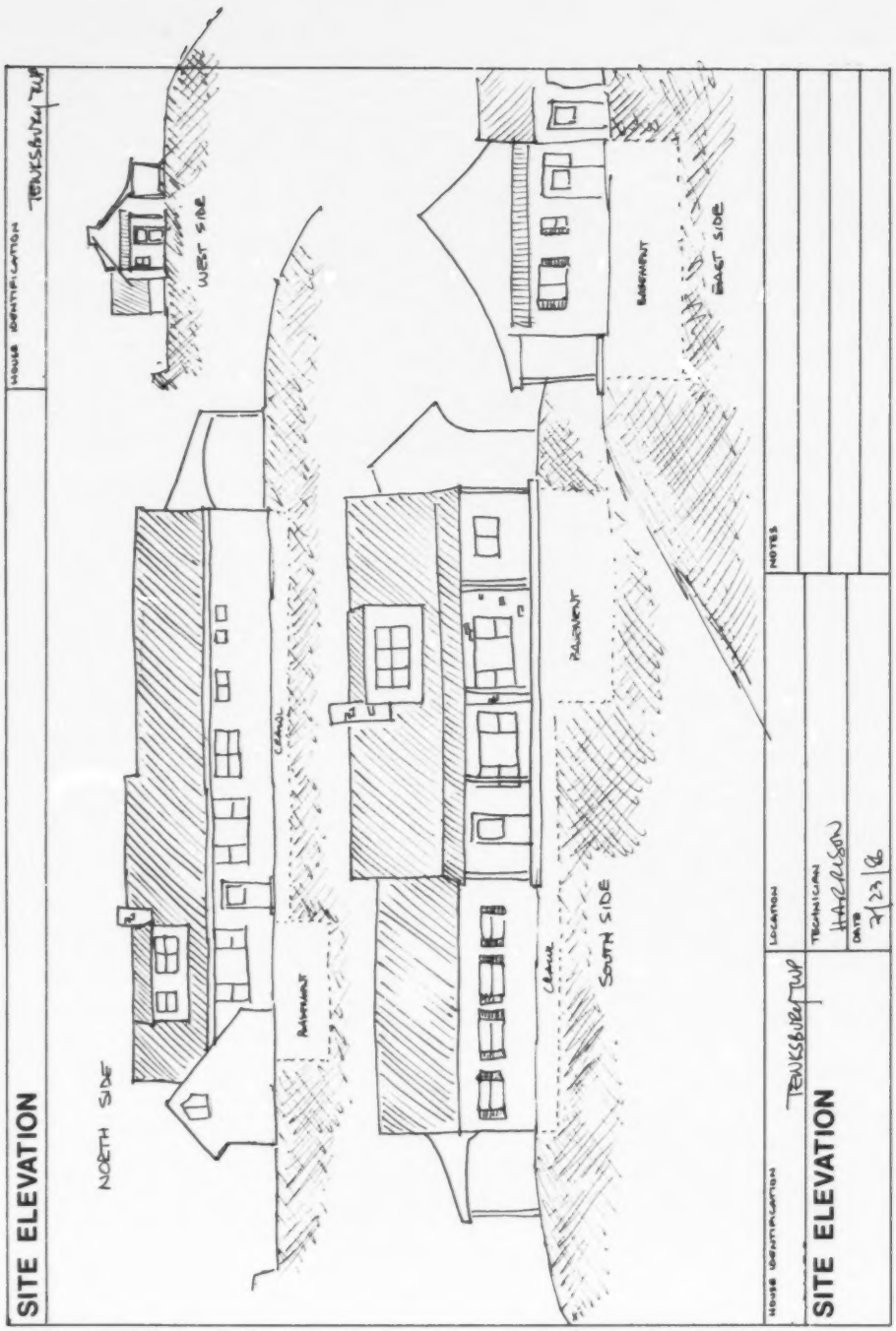
Major appliances located in substructure (crawlspace, slab-on-grade, basement)

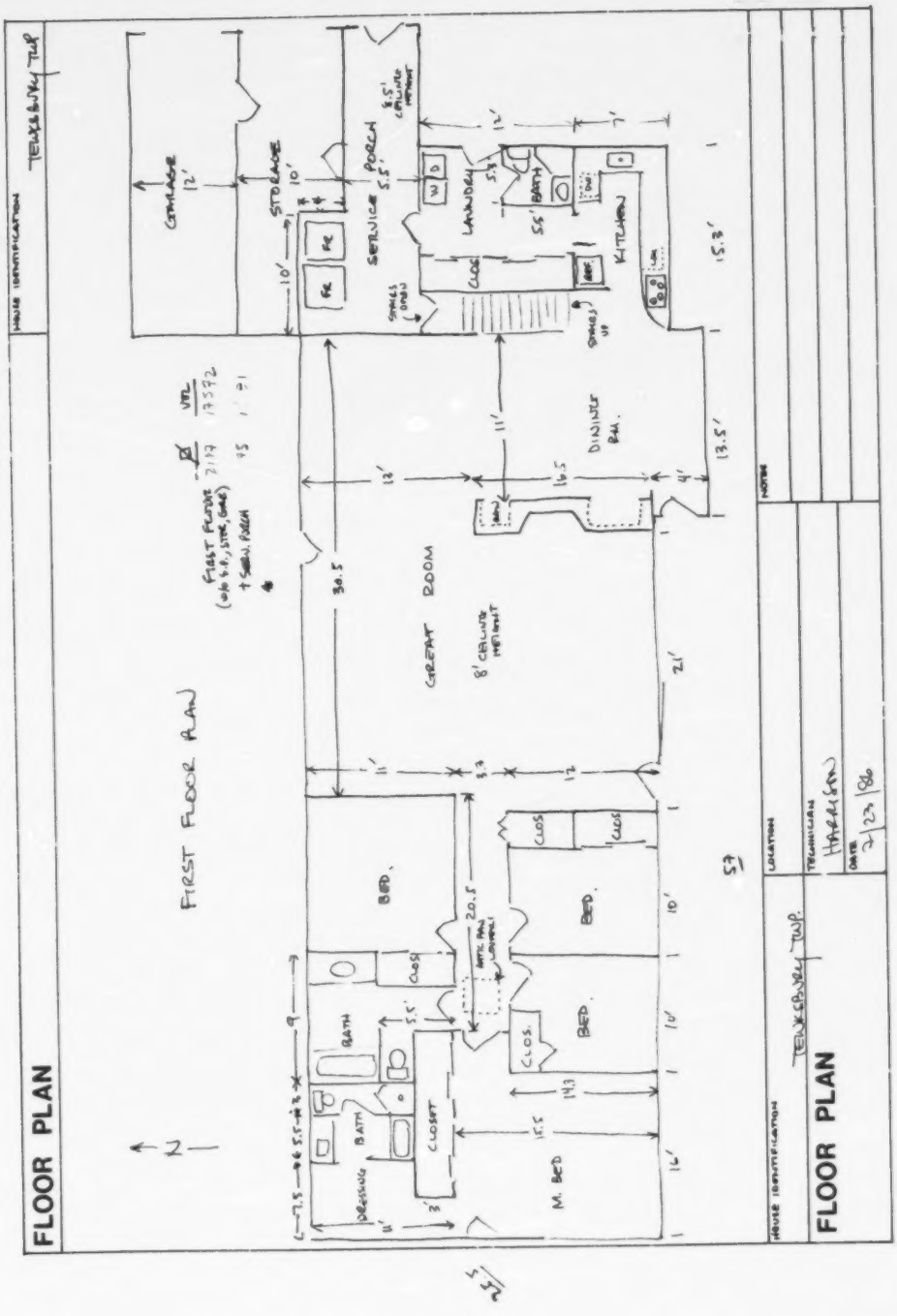
Appliance	Location (Crawl, Slab, Base)	Description (Fuel type, style, operation)
Furnace		
Water Heater		
Air Conditioner		
Clothes Dryer		
Exhaust Fans		
Other:		

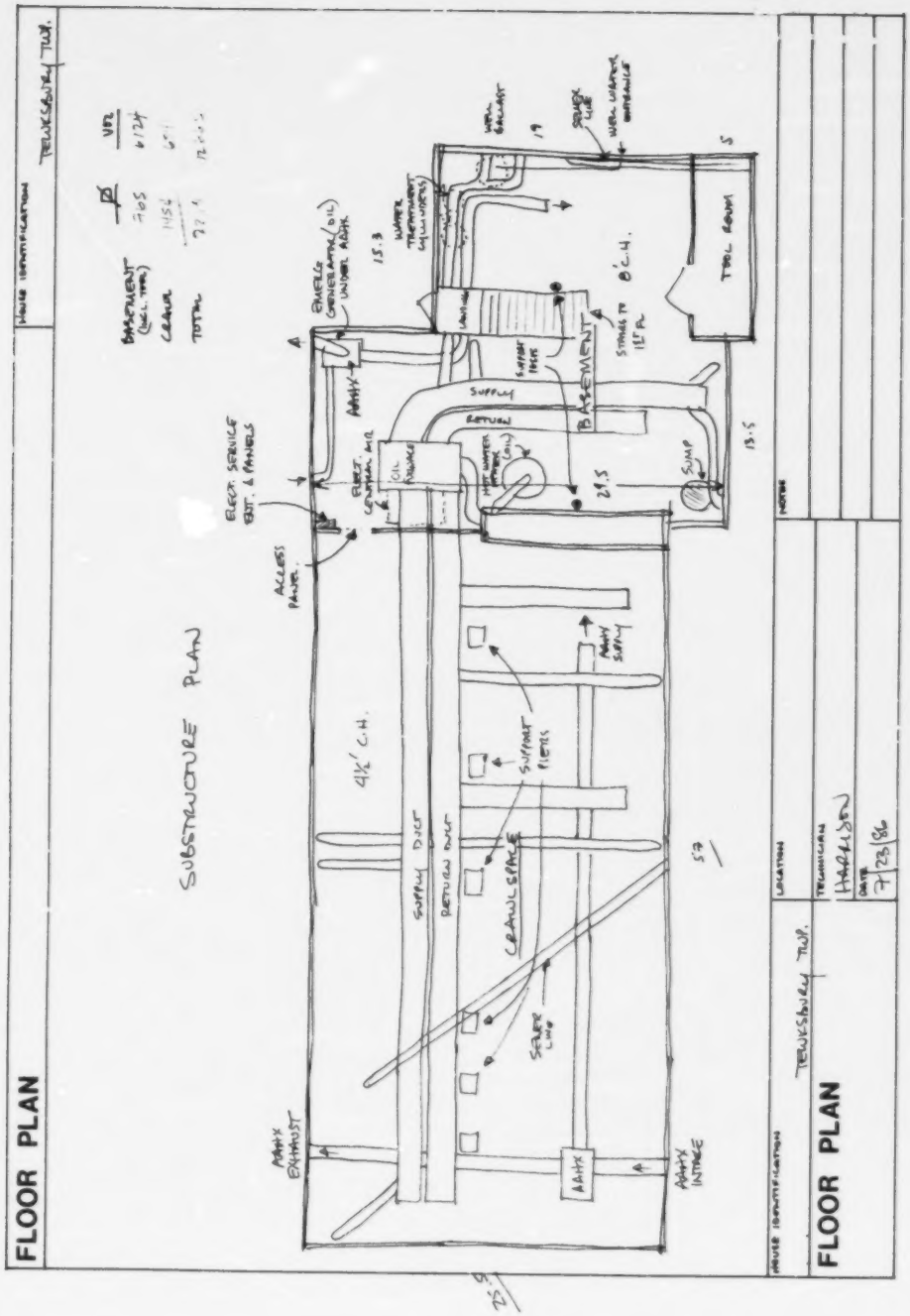
Forced air duct/plenum seals - describe

Combustion Appliances: combustion air supplied (yes, no)


SITE PLAN
HOUSE IDENTIFICATION
TROUTSBURG TWP
N
WOODED AREA
100' HIGH CANOPY
SLOPE
120'
PASTURE
SLOPE
SLOPE
BARN
TERRACE
LEVEL
SLOPE
HEAVILY WOODED AREA
SLOPE
SLOPE
LEVEL
SLOPE
50'
50'
SLOPE
LEVEL
PASTURE
SLOPE
SLOPE
DRIVE
NOTES
LOCATION
TROUTSBURG TWP
TOWNSHIP
HATTAN
DATE
2/23/82
SITE PLAN


SITE ELEVATION
HOUSE IDENTIFICATION
TEWKESBURY TWP
NORTH SIDE
WEST SIDE
EAST SIDE
SOUTH SIDE
BASEMENT
CANAL
LOCATION
NOTES
TECHNICIAN
HARRISON
DATE
7/23/86

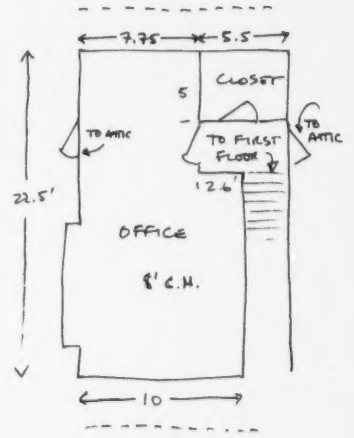

FLOOR PLAN
HOUSE IDENTIFICATION
TEWKSBURY TWP
FIRST FLOOR PLAN
GREAT ROOM
8' CEILING HEIGHT
DINING RM.
KITCHEN
LAUNDRY
SERVICE PORCH
STORAGE
GARAGE
BED.
M. BED
CLOS.
BATH
DRESSING
CLOSET
FIRST FLOOR
LOCATION
TECHNICIAN
DATE
NOTES
FLOOR PLAN


FLOOR PLAN
HOUSE IDENTIFICATION
TEWKESBURY TWP.
SUBSTRUCTURE PLAN
BASEMENT
CRAWL
TOTAL
BASEMENT
CRAWL SPACE
SUPPLY DUCT
RETURN DUCT
SUPPORT PIERS
SUMP
ELECT. SERVICE ENT. & PANELS
ACCESS PANEL
AAHX EXHAUST
AAHX INTAKE
TOOL ROOM
WATER TREATMENT EQUIPMENT
FLOOR PLAN
HOUSE IDENTIFICATION
TEWKESBURY TWP.
LOCATION
NOTES
TECHNICIAN
HAGLSON
DATE
7/23/86

FLOOR PLAN

HOUSE IDENTIFICATION: TEWKSBURY TWP

SECOND FLOOR



☑	VOL
300	2400

HOUSE IDENTIFICATION	LOCATION	NOTES
TEWKSBURY TWP.		
FLOOR PLAN	TECHNICIAN: HARRISON	
	DATE: 7/23/86	

RADON GAS SAMPLING LOG

Occupant Name _____ House ID# _____

Technician _____ Date _____

LUCAS CELL MEASUREMENTS

Sample Number	1	2	3
Lucas Cell ID#			
Tests since last background (new background after 10 tests)			
Background rate (cts/min)			
Sampling:	[] Indoor [] Outdoor	[] Indoor [] Outdoor	[] Indoor [] Outdoor
Sample Location			
Date/Time sample collected	/	/	/
Analysis	- MINIMUM 30 MIN. DELAY -		
Counting Instrument			
Date/Time started	/		/
Elapsed Delay Time (minutes)			
	Count to 1000, stop at next minute, 10 minute Maximum		
Time Stop			
Total Counts			
Elapsed Counting Time (min)			
Concentration			

Sample Number	4	5	6
Lucas Cell ID#			
Tests since last background (new background after 10 tests)			
Background rate (cts/min)			
Sampling:	[] Indoor [] Outdoor	[] Indoor [] Outdoor	[] Indoor [] Outdoor
Sample Location			
Date/Time sample collected	/	/	/
Analysis	- MINIMUM 30 MIN. DELAY -		
Counting Instrument			
Date/Time started	/		/
Elapsed Delay Time (minutes)			
	Count to 1000, stop at next minute, 10 minute Maximum		
Time Stop			
Total Counts			
Elapsed Counting Time (min)			
Concentration			

RADON GAS SAMPLING LOG

Occupant Name _____ House ID# _____

Technician _____ Date _____

LUCAS CELL MEASUREMENTS

Sample Number	1	2	3
Lucas Cell ID#			
Tests since last background (new background after 10 tests)			
Background rate (cts/min)			
Sampling:	[] Indoor [] Outdoor	[] Indoor [] Outdoor	[] Indoor [] Outdoor
Sample Location			
Date/Time sample collected	/	/	/
Analysis	- MINIMUM 30 MIN. DELAY -		
Counting Instrument			
Date/Time started	/		/
Elapsed Delay Time (minutes)			
	Count to 1000, stop at next minute, 10 minute Maximum		
Time Stop			
Total Counts			
Elapsed Counting Time (min)			
Concentration			

Sample Number	4	5	6
Lucas Cell ID#			
Tests since last background (new background after 10 tests)			
Background rate (cts/min)			
Sampling:	[] Indoor [] Outdoor	[] Indoor [] Outdoor	[] Indoor [] Outdoor
Sample Location			
Date/Time sample collected	/	/	/
Analysis	- MINIMUM 30 MIN. DELAY -		
Counting Instrument			
Date/Time started	/		/
Elapsed Delay Time (minutes)			
	Count to 1000, stop at next minute, 10 minute Maximum		
Time Stop			
Total Counts			
Elapsed Counting Time (min)			
Concentration			

SOIL PERMEABILITY SURVEY

HOUSE I.D. _____

NAME _____ TECHNICIAN _____

ADDRESS _____ DATE _____

SAMPLE NO.	1	2	3
LOCATION	AIR TEMPERATURE:	AIR TEMPERATURE:	AIR TEMPERATURE:
DESCRIPTION	DEPTH / MOISTURE: ☐ DRY ☐ MOIST ☐ WET / TEXTURE: ☐ FINE ☐ SANDY ☐ COARSE ☐ _____	DEPTH / MOISTURE: ☐ DRY ☐ MOIST ☐ WET / TEXTURE: ☐ FINE ☐ SANDY ☐ COARSE ☐ _____	DEPTH / MOISTURE: ☐ DRY ☐ MOIST ☐ WET / TEXTURE: ☐ FINE ☐ SANDY ☐ COARSE ☐ _____
SOIL GAS SAMPLES			
LUCAS CELL I.D.			
PERMEABILITY			
PRESSURES	1 2 3	1 2 3	1 2 3
ROTAMETER I.D.			
ROTAMETER READINGS	1. 2. 3. X		
FLOW RATE			
K cm²			
COMMENTS			

SAMPLE NO.	4	5	6
LOCATION	AIR TEMPERATURE:	AIR TEMPERATURE:	AIR TEMPERATURE:
DESCRIPTION	DEPTH / MOISTURE: ☐ DRY ☐ MOIST ☐ WET / TEXTURE: ☐ FINE ☐ SANDY ☐ COARSE ☐ _____	DEPTH / MOISTURE: ☐ DRY ☐ MOIST ☐ WET / TEXTURE: ☐ FINE ☐ SANDY ☐ COARSE ☐ _____	DEPTH / MOISTURE: ☐ DRY ☐ MOIST ☐ WET / TEXTURE: ☐ FINE ☐ SANDY ☐ COARSE ☐ _____
SOIL GAS SAMPLES			
LUCAS CELL I.D.			
PERMEABILITY			
PRESSURES	1 2 3	1 2 3	1 2 3
ROTAMETER I.D.			
ROTAMETER READINGS	1. 2. 3. X		
FLOW RATE			
K cm²			
COMMENTS			

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LBL/BPA FAN TEST DATA SHEET

Occupant Name _____ House ID No. _____

Address _____

_____ Blower Door S/N or Descrip. _____

Technician: _____ Date _____

Monitoring Period _____

BUILDING DIMENSIONS

FIRST FLOOR		SECOND FLOOR	
Floor Area	_____ (ft^2)	Floor Area	_____ (ft^2)
Ceiling Height	_____ (ft^3)	Ceiling Height	_____ (ft^3)
Volume	_____ (ft^3)	Volume	_____ (ft^3)

Total Area _____ (ft^2)

Total Volume _____ (ft^3)

Overall Height of Occupied Floors* _____ (ft)

* Include basement or attic only if occupied

ENVIRONMENTAL DATA

Outdoor: Temperature _____ F

Wind Speed _____ MPH

Terrain Parameters (Table on back)

Indoor: Temperature:

Dry Bulb: _____ F

Wet Bulb: _____ F

Relative Humidity: _____ %

Shielding Class _____

Terrain Class _____

Shut-Off Combustion Appliances TEST DATA

Flow Pressure

House Δ P (Pascals)	0-120 (Pascals) UP	0-120 (Pascals) DOWN	120-750 (Pascals) UP	120-750 (Pascals) DOWN
60/				
55/				
50/				
45/				
40/				
35/				
30/				
25/				
20/				
15/				

Note: Use "down" data for calculations if "up" and "down" are different.

Leakage Coefficients (Table on back)

R = _____ $\{ \frac{Lc + Lf}{Lt} \}$

X = _____ $\{ \frac{Lc - Lf}{Lt} \}$

Fan Location _____

Fan Configuration (11,10,5) _____

Correlation _____ %

Standard Error _____

ELA:LBL _____ in^2

LBL Use

SLA _____

ACH (4 Pa) _____

ACH (50 Pa) _____

ENVELOPE CONDITIONS

Fireplace Sealed _____ Dryer Vent _____ Exhaust Fans _____

Woodstove Sealed _____ Combustion Air _____ Furnace Flue _____

Include area (in^2) of other sealed areas _____

Comments: _____

_____

IMPORTANT: PILOT LIGHTS: Water Heater _____ Furnace _____

Lawrence Berkeley Laboratory 8-28-86

TABLE 1

TERRAIN PARAMETERS

Class	y	a	Description
I	0.10	1.30	Ocean or other body of water with at least 5 km of unrestricted expanse
II	0.15	1.00	Flat terrain with some isolated obstacles (e.g., buildings or trees well separated from each other)
III	0.20	0.85	Rural areas with low buildings, trees, etc.
IV	0.25	0.67	Urban, industrial or forest areas
V	0.35	0.47	Center of large city (e.g. Manhattan)

SHIELDING COEFFICIENTS

Shielding Class	C	Description
I	0.324	No obstructions or local shielding whatsoever
II	0.285	Light local shielding with few obstructions
III	0.240	Moderate local shielding, some obstructions within two house heights
IV	0.185	Heavy shielding, obstructions around
V	0.102	Very heavy shielding, large obstruction surrounding perimeter within two house heights

TABLE OF R AND X VALUES

	House Condition		
House Type	Loose Windows & Doors (R,X)	Average Windows and Doors (R,X)	Tight Windows and Doors (R,X)
1 story (slab)	.3,.3	.4,.4	.5,.5
1 story (basement or crawl)	.5,0	.66,0	.8,0
2 story (slab)	.2,.2	.3,.3	.4,.4
2 story (basement or crawl)	.4,0	.5,0	.6,0

BUILDING MATERIALS SAMPLING LOG

NAME _____ HOUSE ID# _____

ADDRESS _____ TECHNICIAN _____

_____

SURFACE *

Location (Note on Floor Plan)					
Deploy: Date					
Time					
Remove: Date					
Time					
Distance From _____ Wall					
Inches					
Distance From Floor					
Depth Below Grade					
Canisters: #1					
#2					
Descriptions: Material					
Surface Finish					
Comments					

* Surface Types:

Wall 1, 2, 3 ...
Floor 1, 2, 3 ...
Other 1, 2, 3 ...

Page ___ of ___

SOIL SAMPLE LOG

Name _____
Address _____
_____

House I.D. _____
Technician _____
Date _____

Soil Samples

Sample No. / Location (identify on plan) / Depth	A	B	C	D	E	F	G	H	I	J
Time										
Location (identify on plan)										
Depth										
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
Comments:										

8/29/86

Page ___ of ___

WATER SAMPLES LOG

Name _____
Address _____
_____

House I.D. _____
Technician _____
Date _____

	H1	H2	H3	H4
Collection: Date:				
Time:				
Faucet Location				
Water Supply				
Comments:				

8/29/86